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# IGNEOUS ROCKS

COMPOSITION, TEXTURE AND CLASSIFICATION
DESCRIPTION AND OCCURRENCE

BY

JOSEPH P. IDDINGS

IN TWO VOLUMES

VOLUME I

*FIRST EDITION*
FIRST THOUSAND

NEW YORK
JOHN WILEY & SONS
LONDON: CHAPMAN & HALL, LIMITED
1909

Stanhope Press
F. H. GILSON COMPANY
BOSTON, U.S.A.

# PREFACE

The advancement in the knowledge of chemical and physical laws controlling the behavior of solutions has been so material, and the application of these laws to the problems of petrology is so vital to a correct understanding of the fundamental characters of igneous rocks, that the study of such rocks should be conducted along lines closely in accord with the chemical and physical principles mentioned. Moreover, the methods of investigating rocks have so greatly improved, and are yielding such an increasing store of geological, mineralogical, and chemical data, and such an enlarged knowledge of the rocks themselves, that a more comprehensive view is possible of the field of igneous petrology and of the scope of the problems involved in its development.

The thorough study of favorable occurrences of igneous rocks in various parts of the world has furnished reasonable basis for extensive generalizations, and the laboratory study of many kinds of material has provided valuable information of a chemical and mineralogical nature. Notable advances are being made in the physical and chemical investigation of rock minerals and rocks, the most important of which are those carried on in the Geophysical Laboratory of the Carnegie Institution of Washington. The synthetical researches of Day and his colleagues, as well as those of Vogt, Doelter, Morozewicz, and others are carrying forward the earlier work of Daubrée, Fouqué and Michel-Lévy, and are establishing the laws of formation of the mineral constituents of igneous rocks.

Recognition of the character of igneous magmas as solutions has opened the way for the application of modern conceptions of physical chemistry to the elucidation of the phenomena of crystallization, and of genetic relationships among igneous rocks. Foremost among those who have attempted such an application is Vogt, following the lead of Bunsen. The result of these advances has been the shifting of the point of view of the student

of petrology, and the need of changing the line of attack on the problems presented.

For these reasons it has been thought advisable to adopt a new method of treating the subject of igneous rocks; one that assumes an elementary acquaintance with rocks on the part of the student, which may be acquired in courses in general geology; and which begins with the most fundamental and essential character of igneous rocks, their chemical composition. This character is considered in terms of the component elements, and of the compounds, or minerals, in which the elements combine.

To account for the production of these compounds, and for their separation from magma solutions, and their crystallization into rocks, the probable physical and chemical characters of rock magmas are discussed with reference to known physico-chemical laws regarding solutions. These are set forth in some detail in order to bring them clearly before the mind of the student; special application of the laws of chemical reactions being made to a magma of average composition. When the presence in a magma of certain compounds has been recognized as probable, their separation from solution, and their crystallization are of next moment. This leads to a consideration of the texture of igneous rocks. And further application of chemical and physical laws to conditions of equilibrium in rock magmas introduces the subject of the differentiation of magmas and the origin of variation in igneous rocks, which is followed logically by the problem of their eruption and solidification as rock bodies.

Having acquired a knowledge of the general principles applicable to all igneous rocks, it is in order to consider specifically those occurring in all known parts of the earth; systematically in the first instance, and afterwards according to groups as they occur in different regions, or petrographical provinces. But to do this a nomenclature is necessary, and some system of classification. To understand the confusion existing in the systems in use at present a brief historical review of the growth of petrography is given. This is followed by a summary of the Qualitative Mineralogical Classification of igneous rocks in general use, and by a statement of the Quantitative System of Classification. The descriptive portion of the work is to constitute a second volume.

In the construction of Volume I, liberal use has been made of many sources of information, to which references are given in most cases. But the subject is so complex that the present treatment of it must be necessarily incomplete. However, it is hoped that the essential features of the petrology of igneous rocks have been presented in such a manner as to inform the student of the fundamental facts of the subject, and to call his attention to the lines along which further advancement of the science may be made.

I am under special obligations to Dr. Arthur L. Day of the Geophysical Laboratory of the Carnegie Institution of Washington, and to Professor Alexander Smith of the University of Chicago. And my thanks are due to Professor George P. Merrill of the National Museum; to Dr. E. O. Hovey of the American Museum of Natural History; and to Dr. Whitman Cross, and other friends, of the United States Geological Survey, who have generously permitted the use of photographs for illustrations.

To my colleagues in petrology, Dr. Whitman Cross, Professor Louis V. Pirsson, and Dr. Henry S. Washington, I am indebted for much that appears in many parts of the book. The intimate association sustained with these workers in the same field of research, especially in the development of the System of Quantitative Classification of Igneous Rocks, has so blended ideas and conceptions of the character of rock magmas, and of the essential features of igneous rocks, that it is difficult to dissociate myself from a feeling of joint responsibility with them for most of the contents of this volume. There is in fact common authorship in the subject matter of the chapter on the Quantitative System of Classification, and in a great part of that in the chapter on the texture of igneous rocks; chapters based on our joint publications on these subjects. And to these colleagues and co-workers I dedicate this book in token of friendship and esteem, and in recollection of many days spent in hearty coöperation in the field of constructive petrology.

JOSEPH P. IDDINGS.

WASHINGTON, March 1, 1909.

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# IGNEOUS ROCKS

## PART I

### *CHEMICAL AND MINERAL COMPOSITION AND CONSTITUTION OF IGNEOUS ROCKS*

### CHAPTER I

#### CHEMICAL COMPOSITION OF IGNEOUS ROCKS

**Introduction.** — Although igneous rocks consist in most cases of crystals of several minerals that differ distinctly from one another in composition, but may contain like elements, it is possible to consider the chemical composition of the rock as a whole without regard to its mineral constituents. And this is also admissible because before solidification the mass, in a fluid state, must have existed as a more or less homogeneous liquid. And it may fairly be assumed that the chemical composition of the liquid molten magma, in any given case, was the same as that of the solidified rock, before secondary actions may have produced changes in its composition. The chemical composition of a fresh, unaltered, igneous rock may be considered then as representing the composition of its preëxisting liquid magma, or rock solution, except for the escaped gases.

While in many instances igneous rocks have undergone more or less alteration since their first solidification, there are many instances in which they have experienced so little chemical change that the chemical analysis of the rock undoubtedly represents essentially the chemical composition of the liquid magma from which it solidified. Such slightly altered rocks are known among almost all varieties of igneous rock. The commonest modes of chemical alteration are accompanied by accessions of water, or carbon dioxide, or both; analyses of such rocks may usually be recognized by the presence of abnormal percentages of these constituents. In other cases microscopical study of the rock may reveal the altered condition.

## CHEMICAL DATA

The discussion of the chemical composition of igneous rocks is based on analyses that have been made and published at various times by chemists and petrographers in all parts of the world, and that may be found in widely scattered publications. But the student is fortunate in having at his command almost complete collections of these analyses brought together in accessible tables which may be found in any well-equipped petrographical library. The earlier rock analyses were republished in tabular form by Justus Roth in the Proceedings of the Royal Prussian Academy of Science, in Berlin, and embrace all those that had appeared in print prior to 1884,[1] amounting to 2422. The more reliable of them, 248 in number, have since been rearranged in tabular form by H. S. Washington, and have been republished by the U. S. Geological Survey.[2]

All rock analyses that were published from 1884 to 1900, some 2881, have been tabulated by Washington, and published by the U. S. Geological Survey,[3] and more recent analyses are about to be tabulated and issued in a similar manner. Valuable sources of chemical and mineralogical data relating to igneous rocks are the Bulletins, 168 and 228, of the U. S. Geological Survey,[4] which contain brief descriptions of the mineral composition of most of the rocks that have been analyzed in the laboratories of the Survey.

Comments and criticism of rock analyses and descriptions of the most modern methods of making complete chemical analyses of rocks may be found in the Bulletins just mentioned, in the introduction to the Tables of analyses collected by H. S. Washington,[5] and in works on the subject of rock analysis by W. F. Hillebrand[6] and by H. S. Washington.[7]

[1] Roth, J. Die Gesteins Analysen, etc., Berlin, 1861, and Beiträge zur Petrographie der plutonischen Gesteine, etc. Sitzungsber. K. Preuss. Akad. Wiss., Berlin, 1869, 1873, 1879 and 1884.

[2] Washington, H. S. The Superior Analyses of Igneous Rocks from Roth's Tabellen, etc. U. S. Geological Survey, Prof. Paper, 28, 1904.

[3] Washington, H. S. Chemical Analyses of Igneous Rocks, published from 1884 to 1900, etc. U. S. Geological Survey, Prof. Paper, 14, 1903.

[4] Clarke, F. W. Analyses of Rocks from the Laboratory of the U. S. Geological Survey, etc. Bulletin, 168, 1900, and 228, 1904.

[5] *Loc. cit.*, pp. 16–43.

[6] Hillebrand, W. F. Some Principles and Methods of Rock Analysis. U. S. Geological Survey, Bulletin, 176, 1900.

[7] Washington, H S. Manual of the Chemical Analysis of Rocks. New York and London, 1904.

General discussion of the chemical composition of igneous rocks may be found in the publications of Roth, just mentioned, and in monographs and text-books cited below:

Rosenbusch, H. Über die chemischen Beziehungen der Eruptivgesteine. Tscher. min. petr. Mitth., 1889, xi, 144, and, Elemente der Gesteinslehre, Stuttgart, 1898.

Zirkel, F. Lehrbuch der Petrographie. Leipzig, 1893, vol. 1, pp. 649–679.

Roth, J. Allgemeine und Chemische Geologie. Berlin, 1887, vol. 2, pp. 57 67.

Osann, A. Tscher. min. petr. Mitth., vol. 19, p. 351, 1900; vol. 20, p. 399, 1901; vol. 21, p. 365, 1902; vol. 22, pp. 322, 403, 1903.

Loewinson-Lessing, F. Compt. Rend. VII Cong. géol. internat., 1897.

Washington, H. S. U. S. Geological Survey, Professional Paper, 14, 1903.

Iddings, J. P. U. S. Geological Survey, Professional Paper, 18, 1903.

Clarke, F. W. The Data of Geochemistry. U. S. Geological Survey, Bulletin 330. 1908, pp. 352–400.

**Constituent Elements.** — A study of these data shows that there are a few elements almost always present in notable amounts in igneous rocks; others that are often present in traces, occasionally in notable amounts; while most of the remaining known chemical elements are seldom if ever recorded in chemical analyses, but have been noted in exceptional occurrences, or as present in rare minerals found chiefly in pegmatite veins, which are undoubtedly forms of igneous rock not usually analyzed in bulk.

The commonly occurring elements, usually in notable amounts, are oxygen (O), silicon (Si), aluminium (Al), iron (Fe), magnesium (Mg), calcium (Ca), sodium (Na), potassium (K), hydrogen (H), and titanium (Ti). With these are associated in still smaller amounts, or in traces, zirconium (Zr), thorium (Th), cerium (Ce), didymium (Di), lanthanum (La), phosphorus (P), vanadium (V), fluorine (F), chlorine (Cl), sulphur (S), carbon (C), boron (B), nitrogen (N), chromium (Cr), manganese (Mn), nickel (Ni), cobalt (Co), barium (Ba), strontium (Sr), glucinum (Gl), lithium (Li), cæsium (Cs), rubidium (Rb), yttrium (Y), and other members of this group of elements, uranium (U), columbium (Cb), tantalum (Ta). Besides these are sometimes found: tin (Sn), lead (Pb), copper (Cu), silver (Ag), gold (Au), zinc (Zn), bismuth (Bi), antimony (Sb), arsenic (As). In fact it is to be expected that most all elements may be found somewhere in igneous rocks, and in such a manner as to appear to

have been a constituent of the molten magma. It is to be observed, however, that most rock analyses do not take notice of most of the elements that have just been mentioned. Their presence in rocks is often inferred from that of rare minerals in which they are known to occur. Or as already said, they may occur in minerals in coarse-grained pegmatites.

The one element that is universally present in notable amounts in igneous rocks as at present known is oxygen. All the others may be in some varieties of rocks reduced to mere traces, but in the vast majority of igneous rocks there are notable amounts of oxygen, silicon, aluminium, iron, magnesium, calcium, sodium, potassium, with smaller but measurable amounts of hydrogen, titanium, and phosphorus.

**Chemical Constituents.** — These are recorded in statements of analyses as oxides: $SiO_2$, $TiO_2$, $Al_2O_3$, $Fe_2O_3$, FeO, MgO, CaO, $Na_2O$, $K_2O$, $H_2O$, $P_2O_5$; and in the discussion which follows and frequently throughout the book the chemical components of rocks or of liquid magmas will be referred to as oxides, though they may also be spoken of as simple elements or as more or less complex compounds, chiefly silicates.

A glance at the thousands of analyses of igneous rocks will impress one with the fact that there is the greatest variation in the proportions of the chemical constituents, and that there are scarcely two analyses exactly alike, though many resemble one another closely. Furthermore, it appears that with the exception of a very few cases there are no simple, or definite, stoichiometric proportions between the components. In other words, an analysis does not represent a single chemical compound, but a mixture of two or more compounds.

**Representative Analyses.** — Without attempting to illustrate the variability of composition of igneous rocks by the introduction in this place of a great number of chemical analyses, which may be found in the publications already mentioned, it may be well to cite a few that represent some of the possible cases. They are shown in the accompanying table and illustrate some of the extremes and intermediate cases.

1. Alaskose (I, 3, 1, 3) rhyolite, Montgomery Co., N. C. W. T.[1] p. 126.
2. Magdeburgose (I, 3, 1, 2) granite, Pike's Peak, Colo. W. T. p. 124.
3. Tuolumnose (I, 5, 1, 5) syenite, Tuolumne Co., Cal. W. T. p. 198.
4. Nordmarkose (I, 5, 1, 4) pulaskite, Farris, Norway. W. T. p. 196.
5. Nordmarkose (I, 5, 1, 4) litchfieldite, Litchfield, Me. W. T. p. 194.
6. Beemerose (I, 6, 1, 3) nephelite-syenite, Beemersville, N. J. W. T. p. 206.
7. Labradorose (I, 5, 4, 3) anorthosite, Carlton Peak, Minn. W. T. p. 204.
8. Urtose (II, 9, 1, 4) urtite, Kola, Finland. W. T. p. 306.
9. Uralose (I, II, 2, 5, 1, 3) corundum-pegmatite, Ilmen Mountains, Siberia. W. T. p. 216.
10. Kyschtymase (I, III, 1, 5, 5) kyschtymite, Ural Mountains, Siberia. W. T. p. 216.
11. Varingose (II, 3, 1, 3) grorudite, Varingskollen, Norway. W. T. p. 218.
12. Rockallose (III, 3, 1, 5) rockallite, Rockall Island, North Atlantic. W. T. p. 310.
13. Pantellerose (II, 4, 1, 4) pantellerite, Pantelleria. W. T. p. 220.
14. Harzose (II, 4, 3, 3) granite, Butte, Mont. W. T. p. 228.
15. Tonalose (II, 4, 3, 4) average igneous rock, United States. W. T. p. 230.
16. Tonalose (II, 4, 3, 4) andesite, Madison Co., Mont. W. T. p. 233.
17. Placerose (II, 4, 3, 5) mica-diorite, Mazaruni District, British Guiana. W. T. p. 244.
18. Orendose (III, 5, 1, 1) orendite, Leucite Hills, Wyo. W. T. p. 312.
19. Andose (II, 5, 3, 4) basalt, Kilauea, Hawaii. W. T. p. 282.
20. (III, 6, 4, 3) ariegite, Lherz, Pyrenees, France. W. T. p. 346.
21. (V, I, 1, 1, 1, 1, 1), enstatite-pyroxenite, Central Marico District, Transvaal. W. T. p. 366.
22. Websterose (V, I, 1, 1, 1, 2, 1) websterite, Hebbville, Md. W. T. p. 366.
23. Brandbergose (IV, 2, 1, 1, 3, 2) pyroxenite, Brandberget, Norway. W. T. p. 358.
24. Dunose (V, 1, 5, 1, 1, 1) peridotite, Olivine Range, New Zealand. W. T. p. 368.
25. Paulose (IV, 2, 2, 1, 3, 2) jacupirangite, Sao Paulo, Brazil. W. T. p. 360.
26. Permose (V, 2, 5, 1, 1, 2) dunite sidéronitique, Koswinsky, Ural Mountains. Recherches géol. et pétrogr. sur L'oural du Nord, Genéve, 1902, p. 128.
27. (V, 3, 1, 1, 1, 2) iron ore, Taberg, Sweden. School of Mines Quarterly, xxi, p. 60.
28. Adirondackiase (IV, 4, 2, 1, 1, 4) titaniferous iron ore, Essex Co., N. Y. W. T. p. 364.
29. (V, 5, 2, 1, 1, 4) magnetite-spinellite, Routivaara, Finland. W. T. p. 368.
30. (V, 5, 2, 1, 1, 5) iron ore, Sanford, N. Y. School of Mines Quarterly, xx, p. 344.

[1] Washington's Tables of chemical analyses.

CHEMICAL ANALYSES OF VARIOUS KINDS OF IGNEOUS ROCKS

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$.... | 79.57 | 74.40 | 67.53 | 64.54 | 60.39 | 53.56 | 49.78 | 45.43 | 40.06 | 16.80 | 74.35 | 73.60 | 67.48 | 64.34 | 59.71 |
| | 1.326 | 1.240 | 1.126 | 1.076 | 1.007 | .893 | .830 | .757 | .668 | .280 | 1.239 | 1.227 | 1.125 | 1.072 | .994 |
| $Al_2O_3$... | 11.41 | 14.43 | 18.57 | 18.13 | 22.57 | 24.43 | 29.37 | 28.77 | 49.05 | 73.40 | 8.73 | 4.70 | 9.70 | 15.72 | 15.41 |
| | .112 | .142 | .182 | .178 | .221 | .240 | .288 | .282 | .480 | .719 | .086 | .046 | .095 | .154 | .151 |
| $Fe_2O_3$... | 0.20 | 0.22 | 1.13 | 2.63 | 0.42 | 2.19 | 0.34 | 3.10 | 0.35 | 0.76 | 5.84 | 13.10 | 7.42 | 1.62 | 2.63 |
| | .001 | .001 | .007 | .016 | .003 | .014 | .002 | .019 | .002 | .005 | .037 | .082 | .046 | .010 | .016 |
| FeO.... | 0.70 | 0.89 | 0.08 | 0.97 | 2.26 | 1.22 | 0.60 | 0.40 | n. d. | n. d. | 1.00 | n. d. | 2.21 | 2.94 | 3.52 |
| | .010 | .012 | .001 | .013 | .031 | .017 | .008 | .006 | | | .014 | | .030 | .041 | .049 |
| MgO.... | tr. | 0.07 | 0.24 | 0.67 | 0.13 | 0.31 | 1.07 | 0.22 | 0.15 | 0.61 | 0.07 | 0.11 | 0.77 | 2.17 | 4.36 |
| | | .002 | .006 | .017 | .003 | .008 | .025 | .006 | .004 | .015 | .002 | .003 | .019 | .054 | .109 |
| CaO.... | 0.21 | 0.58 | 0.55 | 0.62 | 0.32 | 1.24 | 11.86 | 1.86 | 0.30 | 7.26 | 0.45 | 0.37 | 1.45 | 4.24 | 4.90 |
| | .003 | .010 | .010 | .011 | .006 | .022 | .211 | .033 | .005 | .129 | .008 | .006 | .026 | .076 | .087 |
| $Na_2O$... | 3.46 | 1.76 | 11.50 | 6.60 | 8.44 | 6.48 | 4.39 | 16.16 | 3.71 | 0.38 | 4.51 | 6.96 | 7.21 | 2.76 | 3.55 |
| | .056 | .028 | .185 | .107 | .136 | .104 | .071 | .261 | .060 | .006 | .073 | .112 | .116 | .044 | .057 |
| $K_2O$.... | 3.52 | 6.56 | 0.10 | 5.99 | 4.77 | 9.50 | 0.46 | 3.38 | 5.20 | 0.13 | 3.96 | tr. | 2.94 | 4.04 | 2.80 |
| | .037 | .070 | .001 | .064 | .051 | .101 | .005 | .036 | .055 | .001 | .042 | | .031 | .042 | .030 |
| $H_2O+$.. | 0.61 | 0.92 | 0.31 | 0.31 | 0.57 | 0.93 | 1.76 | n. d. | 0.46 | 0.76 | 0.25 | n. d. | 0.96 | 1.01 | 1.52 |
| $H_2O-$.. | 0.18 | 0.15 | 0.15 | | | | | | | | | | | | |
| $TiO_2$.... | 0.11 | 0.12 | 0.07 | tr. | | | none | | | | | | | 0.53 | 0.60 |
| | .001 | .001 | .001 | | | | | | | | | | | .007 | .007 |
| $P_2O_5$.... | tr. | 0.22 | 0.11 | tr. | | | | | | | | | | 0.14 | 0.22 |
| | | .002 | .001 | | | | | | | | | | | 001 | .002 |
| Etc..... | 0.05 | 0.04 | | 0.42 | 0.08 | 0.10 | 0.08 | | | | 0.22 | 0.99 | | 0.30 | |
| | 100.02 | 100.36 | 100.34 | 100.88 | 99.95 | 99.96 | 99.80 | 99.32 | 99.28 | 100.10 | 99.38 | 99.83 | 100.14 | 99.81 | 99.22 |

| | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$.... | 59.48 | 56.63 | 54.08 | 45.61 | 38.58 | 55.23 | 55.14 | 45.05 | 42.39 | 38.38 | 31.84 | 21.25 | 11.73 | 4.08 | 0.87 |
| | .991 | .944 | .901 | .760 | .643 | .921 | .919 | .751 | .707 | .640 | .531 | .354 | .196 | .068 | .014 |
| $Al_2O_3$... | 16.37 | 17.01 | 9.49 | 15.98 | 20.42 | 2.08 | 0.66 | 6.50 | 2.26 | 6.15 | 1.37 | 5.55 | 6.46 | 6.40 | 0.53 |
| | .160 | .164 | .093 | .156 | .200 | .021 | .005 | .064 | .022 | .060 | .014 | .054 | .063 | .063 | .005 |
| $Fe_2O_3$... | 3.21 | 6.15 | 3.19 | 8.25 | 7.60 | 3.94 | 3.48 | 3.83 | 0.35 | 11.70 | 15.63 | 43.45 | 30.68 | 33.43 | 87.60 |
| | .020 | .039 | .020 | .052 | .048 | .025 | .022 | .024 | .002 | .073 | .098 | .272 | .192 | .209 | .614 |
| FeO.... | 3.17 | 2.80 | 1.03 | 11.60 | 5.91 | 6.25 | 4.73 | 7.69 | 10.47 | 8.14 | 14.25 | | 27.92 | 34.58 | |
| | .044 | .039 | .014 | .161 | .082 | .087 | .065 | .107 | .146 | .113 | .199 | | .388 | .480 | |
| MgO.... | 3.29 | 4.08 | 6.74 | 3.75 | 12.93 | 29.29 | 26.66 | 12.07 | 39.19 | 11.47 | 33.10 | 18.30 | 3.35 | 3.89 | |
| | .082 | .102 | .169 | .094 | .323 | .732 | .667 | .302 | .980 | .287 | .827 | .458 | .084 | .097 | |
| CaO.... | 4.88 | 6.83 | 3.55 | 6.42 | 9.43 | 1.68 | 8.39 | 18.82 | 2.33 | 18.60 | 0.91 | 1.65 | 3.95 | 0.65 | |
| | .087 | .121 | .063 | .114 | .168 | .030 | .150 | .336 | .041 | .332 | .016 | .029 | .071 | .011 | |
| $Na_2O$... | 3.30 | 4.48 | 1.39 | 3.50 | 2.29 | | 0.30 | 0.94 | | 0.78 | | | 0.50 | 0.29 | |
| | .053 | .072 | .022 | .056 | .037 | | .005 | .015 | | .013 | | | .008 | .005 | |
| $K_2O$.... | 2.81 | 0.25 | 11.76 | 1.82 | 1.39 | | none | 0.78 | | 0.13 | | | 0.26 | 0.15 | |
| | .030 | .003 | .125 | .020 | .015 | | | .009 | | .001 | | | .003 | .002 | |
| $H_2O+$.. | 2.01 | 1.17 | 2.71 | 0.27 | 1.25 | 1.12 | 0.38 | 2.40 | 1.54 | 0.72 | 2.49 | 2.60 | 0.64 | 1.32 | |
| $H_2O-$.. | | | 0.79 | | | | | | | | | | | | |
| $TiO_2$.... | 0.93 | 0.18 | 2.08 | 1.15 | | 0.44 | tr. | 2.65 | | 4.32 | | 6.30 | 12.31 | 14.25 | 10.91 |
| | .012 | .002 | .026 | .014 | | .006 | | .033 | | 0.54 | | .079 | .154 | .176 | .137 |
| $P_2O_5$.... | 0.41 | 0.28 | 1.35 | 0.72 | | | 0.23 | 0.15 | | 0.17 | | 0.13 | 0.82 | 0.02 | |
| | .003 | .002 | .009 | .005 | | | .002 | .001 | | .001 | | .001 | .006 | | |
| Etc..... | 0.35 | 0.17 | 1.79 | 1.20 | | | 0.39 | | 0.28 | 0.16 | | 0.40 | 0.57 | 0.65 | |
| | 100.21 | 100.02 | 100.40 | 100.27 | 99.80 | 100.03 | 100.36 | 100.88 | 99.51 | 100.72 | 99.59 | 99.63 | 99.19 | 99.71 | 99.91 |

### DIAGRAMMATIC PRESENTATION OF CHEMICAL DATA

There are facts to be brought out in the discussion of these chemical data which necessitate the assembling of large numbers of analyses, and which may be accomplished most effectively by diagrammatic methods. The facts to be noted in addition to the variableness of proportions are the range and limits of variation among the chemical constituents and the absence of special grouping, clustering, or of the preponderance of particular mixtures of compounds in any part of the range of possibilities.

Various methods of expressing the proportions of chemical elements or components in igneous rocks by diagrams have been employed by petrographers at different times and for various specific purposes. In some cases the expressions have been of a general nature, representing averages of rock analyses; in others a single diagram represents a single analysis. In some the components have been compared in groups; in others they are dealt with separately. A brief description of the different methods may be found in Professional Paper, No. 18, of the U. S. Geological Survey,[1] and the principal references are given below.[2]

[1] Iddings, J. P. Chemical Composition of Igneous Rocks Expressed by Means of Diagrams, etc. Prof. Paper, No. 18, U. S. Geological Survey, 1903, pp. 10–16.

[2] Von Waltershausen, W. S. Über die Vulkanischen Gesteine in Sicilien u. Island, etc. Göttingen, 1853.

Reyer, E. Beitrag zur Fusik der Eruptionen, Vienna, 1877, and Theoretische Geologie, Stuttgart, 1888.

Judd, J. W. Volcanoes. New York, 1881, p. 322, Fig. 88.

Iddings, J. P. Bull. Philos. Soc. Washington, Vol. 11, January, 1890, pp. 207 and 211; also Twelfth Ann. Rept. U. S. Geological Survey, 1892, pp. 629 and 649; Mon. U. S. Geological Survey, vol. 32, pt. 2, pp. 119 and 136; Bull. Philos. Soc. Washington, vol. 12, June, 1892; Jour. Geol., vol. 1, 1893, p. 173; Jour. Geol., vol. 6, 1898, pp. 92–111, 219–237.

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Pirsson, L. V. Twentieth Ann. Rept. U. S. Geological Survey, pt. 3, 1900, p. 568 *et seq.*

Lévy, A. M. Bull. Serv. Carte géol., France, vol. 9, No. 57, 1897, p. 38,

**First Type of Diagrams.** — Several types of diagrams are described below in considerable detail because of their somewhat general use by different petrographers, or on account of their importance in aiding the discussions which are to be found in this book.

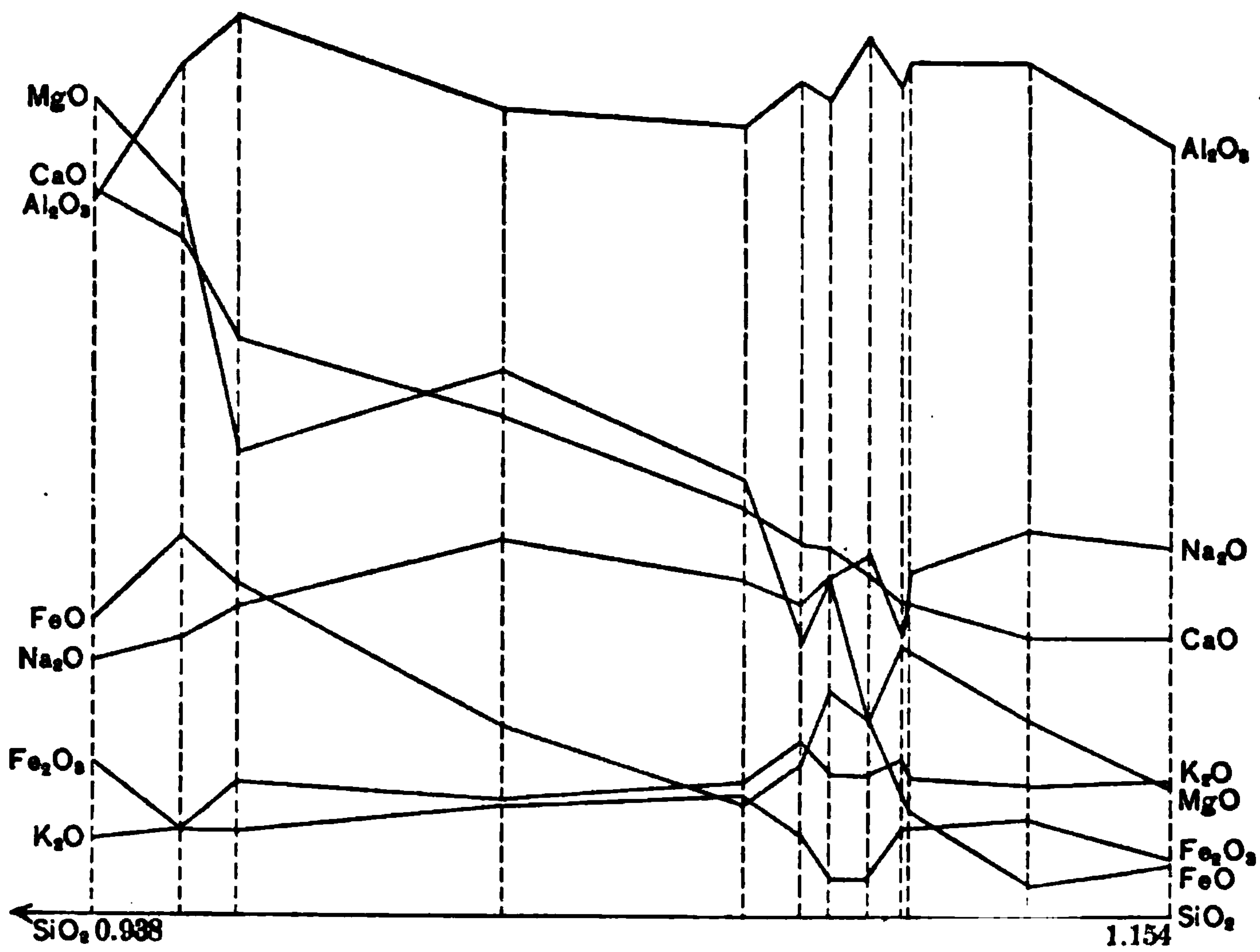


FIG. 1. MOLECULAR VARIATION IN COMPONENTS OF IGNEOUS ROCKS AT ELECTRIC PEAK, Y. N. P.

Among the earlier diagrams one type is that which was used to exhibit by means of crooked lines the variations in the

and Pls. VII, VIII; also Bull. Soc. géol., France, 3d series, vol. 25, 1897, Pls. X to XV; and *idem*, vol. 26, 1898, Pls. III to VI.

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Rosenbusch, H. Elemente der Gesteinslehre, Stuttgart, 1898.

Mügge, O. Neues Jahrb. Min. Geol. und Pal., 1900, vol. 1, pp. 100–112, Pls. V–VII.

Osann, A. Tscher. min. petr. Mitth., vol. 19, 1900, Pls. IV–VIII, XXV; vol. 20, 1901, Pls. VIII–XIV.

Graton, L. C. U. S. Geological Survey, Prof. Paper, 54, 1906, p. 112.

chemical components of the igneous rocks at Electric Peak, Yellowstone National Park.[1] It is shown in Fig. 1. The chemical constituents of each rock analyzed, expressed as oxides in molecular proportions, are compared by means of rectangular coördinates. The silica in each analysis is plotted as an abscissa, the remaining oxides in each analysis being plotted on one vertical ordinate located by the silica abscissas. The constituents of each rock are therefore represented by distances on a vertical line and by the distance apart of these lines. By connecting all the points corresponding to one kind of oxide, such

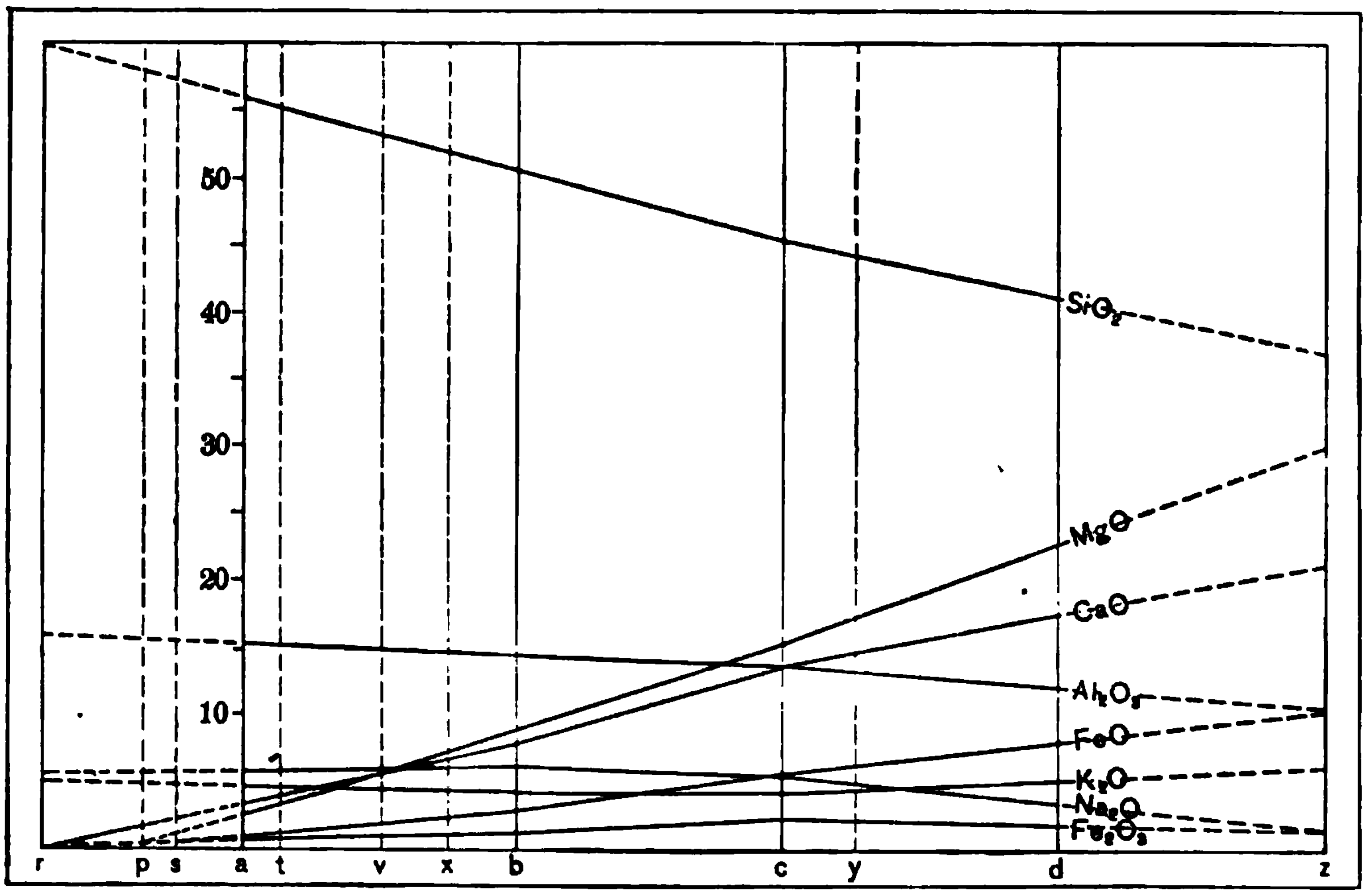



FIG. 2. DIFFERENTIATION DIAGRAM OF LITTLE BELT MOUNTAIN ROCKS. a b c d, ANALYSES OF YOGO PEAK ROCKS; y x v t s p r z, ANALYSES OF NEIGHBORING BODIES OF ROCKS.

as $Al_2O_3$, there is obtained a line which indicates clearly the variations in each of these constituent oxides in passing from one rock to another within the group of rocks under consideration. This form of diagram has been employed by a number of petrographers to indicate the variations in igneous rocks found by chemical analysis. But Harker has used a similar diagram to discuss the possibility of distinguishing igneous rock series from

[1] Iddings, J. P. Twelfth Ann. Rept. U. S. Geological Survey, 1892, p. 629, and elsewhere.

mixed igneous rocks.[1] And Pirsson has employed a slightly modified form of it, which is shown in Fig. 2. In this the abscissas represent distances in one rock body between the various portions of it analyzed, the silica being plotted on the same vertical ordinate as the other components.[2] By this modification of the diagram he showed that the variations in the chemical composition in such a rock body as that at Yogo Peak, lines *a, b, c, d,* follow very regular laws, and with one or two constituents determined in certain varieties of the rock mass the remaining constituents may be found by means of the diagram. He also showed that varieties of the rock intermediate between those analyzed could be estimated from the diagram, and in fact

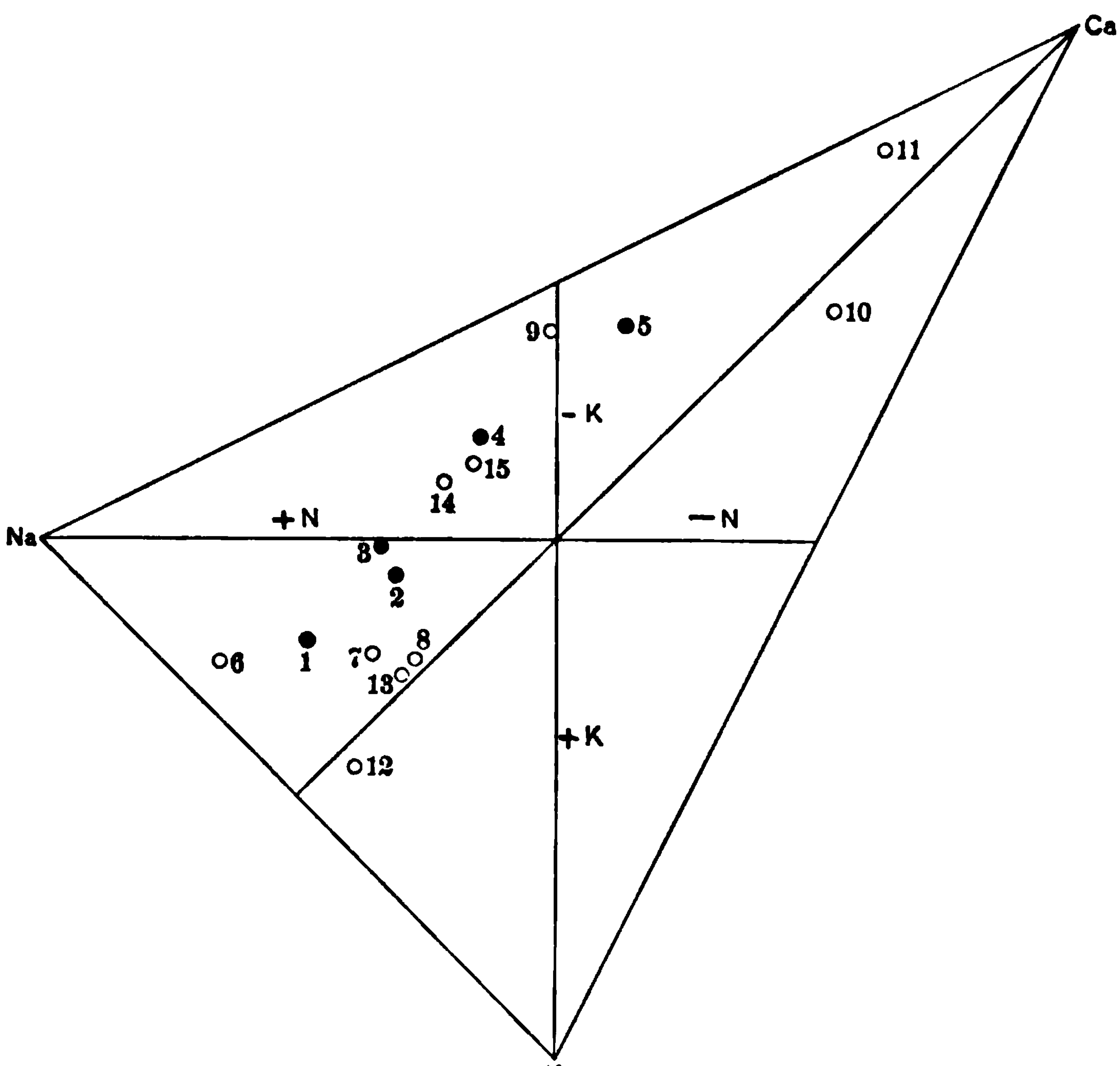



FIG. 3.

that the composition of the igneous rocks of the immediate vicinity, Little Belt Mountains, could be expressed by ordinates in the diagram, as indicated by the lines *r, p, s, t, v, x, y, z*. In

[1] Harker, A. Jour. Geol., vol. 8, 1900, pp. 389–399.

[2] Pirsson, L. V. Twentieth Ann. Rept. U. S. Geological Survey, pt. 3, 1900, p. 571.

this manner he proved that the igneous rocks of that region bear a very simple chemical relation to one another.

**Second Type of Diagrams.** — This consists of spots, one for each analysis, so arranged that their location with reference to coördinate axes indicates the relative proportions of certain constituents or groups of constituents. This was first used by F. Becke[1] in discussing the composition of the rocks of the Columbretes, and the spots were referred to three axes in one plane. The simplest arrangement of axes is given by three lines bisecting the sides of an isosceles triangle, Fig. 3, or of an equilateral triangle. The zero point is at the center of the triangle, and the $k$ axis extends from this to the $K$ angle; the $n$ axis, from the center to the $N$ angle. The three constituents compared with one another in this diagram are Ca, Na, and K. The values of $k$ and $n$ are given by the equations:

$$k = \frac{K - Ca}{Ca + Na + K}, \quad n = \frac{Na + Ca}{Ca + Na + K}.$$

In addition to this triangular diagram, Becke employed another in which spots representing other constituents are located with reference to two coördinate axes, Fig. 4. The plane of the second diagram is perpendicular to that of

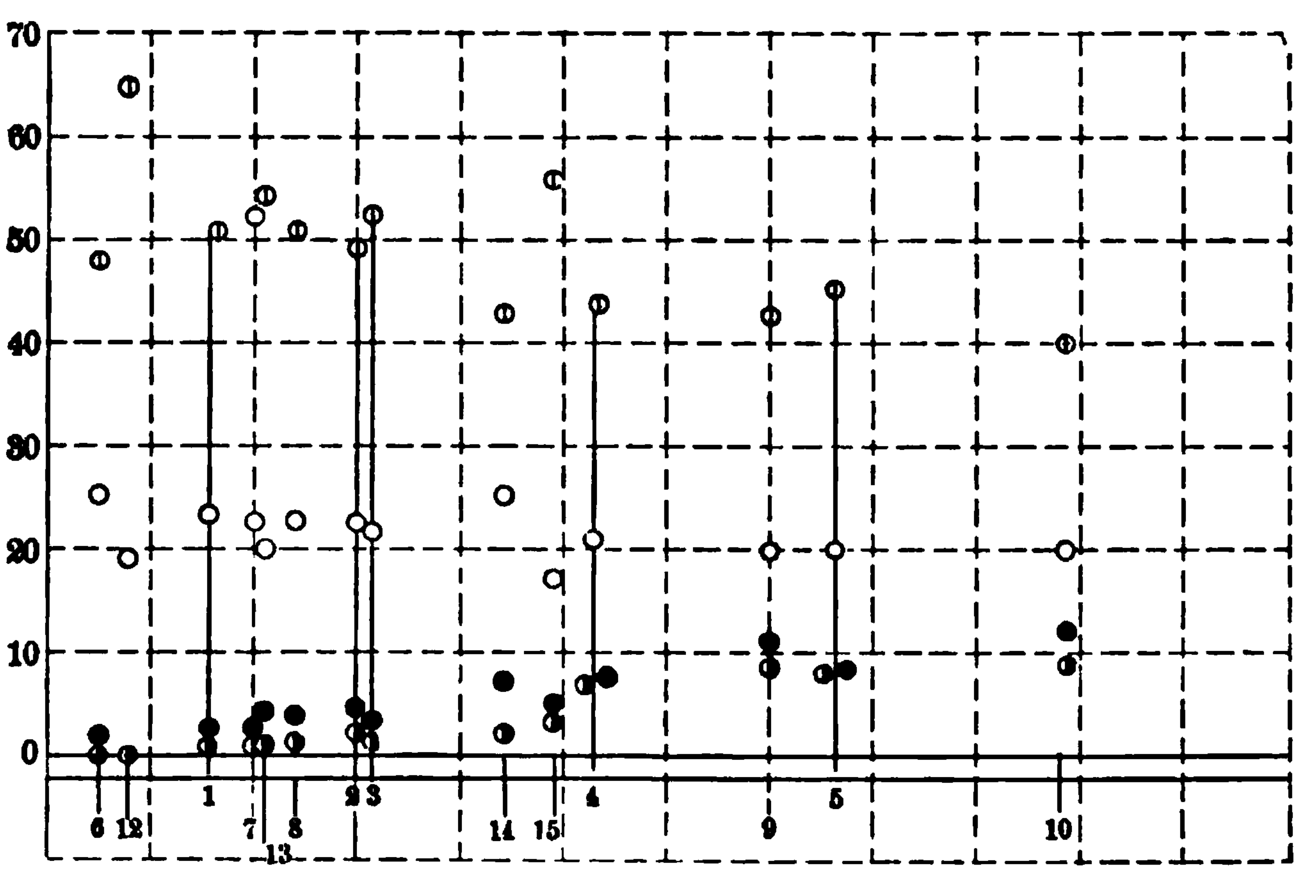



FIG. 4.

the first, and intersects the first along one of the median lines of the equilateral triangle, the Ca line in the diagram used by Becke. The normal projections upon this line of the spots within the triangle give the loci of ordinates in the second plane on which the constituents, Si, Al, Fe, Mg, are plotted. The abscissas on the Ca line are therefore $\frac{Ca}{Ca + Na + K}$ in each case.

The triangular diagram is also used by Osann[2] to locate the analyses of

[1] Becke, F. Tscher. min. pet. Mitth., vol. 16, 1897, pp. 315–320.

[2] Osann, A. *Ibid.*, vol. 19, 1900, Pls. IV–VIII; and vol. 20, 1901, Pls. VIII–XIII.

rocks with respect to the following factors which may be derived from the analyses: A) the $K_2O$ and $Na_2O$ which may be combined with $Al_2O_3$ in equal molecular amounts; C) the CaO which may be combined with the remaining $Al_2O_3$ in equal amounts; F) the sum of the remaining CaO, with MgO and FeO. The sum of the three factors A, C, and F, is in each case reduced to 20, and the factors plotted on this basis.

A somewhat similar type of diagram in which analyses are represented by spots arranged with reference to two coördinate axes was used by the author in discussing the composition of igneous rocks.[1] In this diagram, Fig. 5, which is also shown in the left-hand corner of Plate I, and is used on Plate III, the abscissas are percentages of silica, the zero point being at the right, and the ordinates are the ratios obtained by dividing the

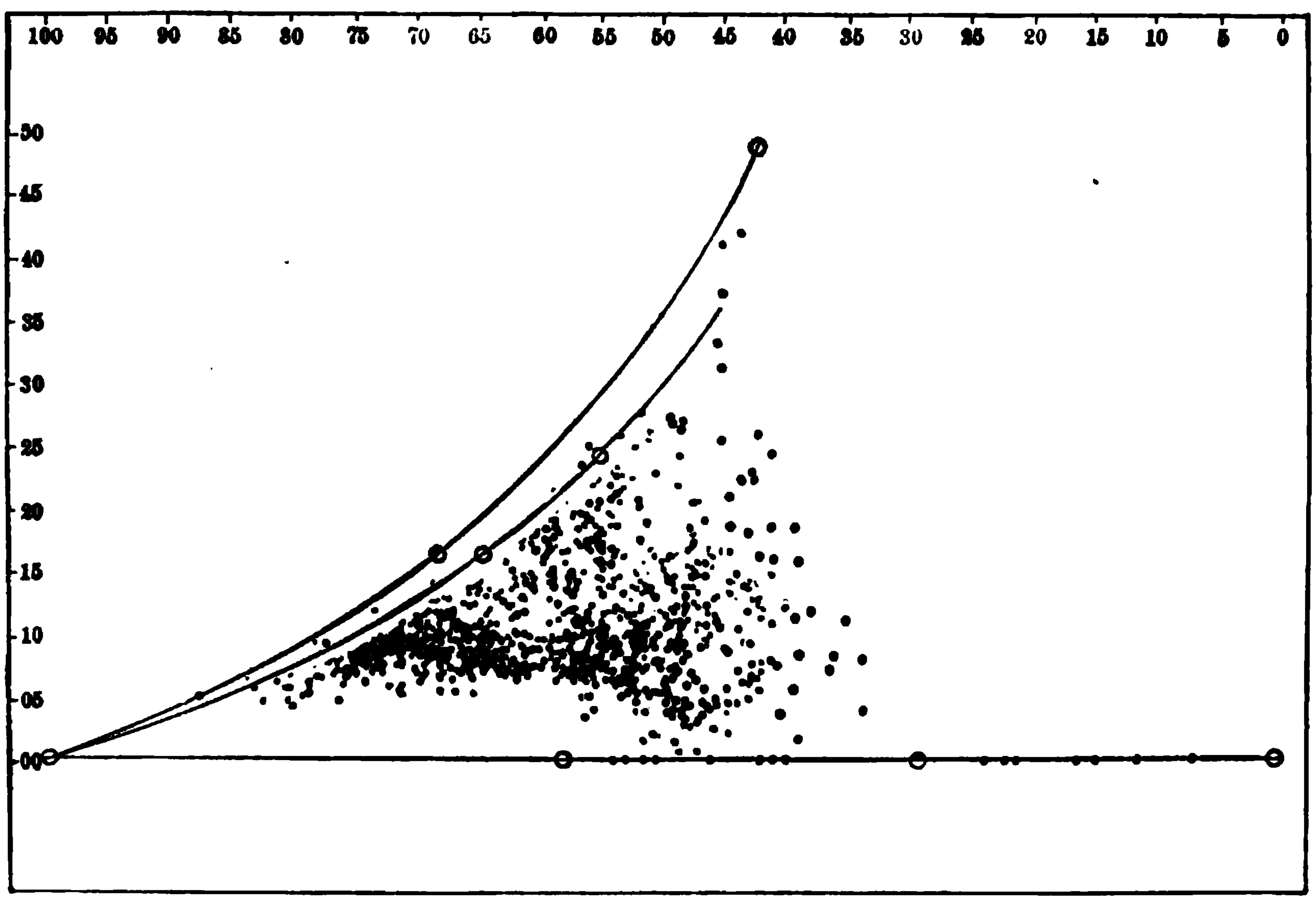



Fig. 5.

sum of the molecular proportions of the alkalies, $K_2O$ and $Na_2O$, by that of silica. The analyses are thus distributed with reference to the silica and the alkalies. This form of diagram is employed in Plates I, II, III, and is discussed on page 19.

A modification of this diagram was used by Michel-Lévy, who introduced a third axis of reference, and plotted the spots, or analyses, with reference to ($x$) the silica percentages in the white component minerals; ($y$) the sum of the percentages of $K_2O$, $Na_2O$, and CaO which may enter feldspars combined

[1] Iddings, J. P. Jour. Geol., vol. 6, 1898, pp. 92–111, 219–237.

with $Al_2O_3$; (*z*) the sum of the percentages of MgO, FeO, $Fe_2O_3$, CaO, and $SiO_2$ in the ferromagnesian components of the rocks.[1]

**Third Type of Diagrams.** — This expresses by the shape of a geometrical figure the relative proportions of the chemical constituents in a single rock analysis. Several methods of construction have been devised. That by Michel-Lévy[2] is shown in Fig. 6.

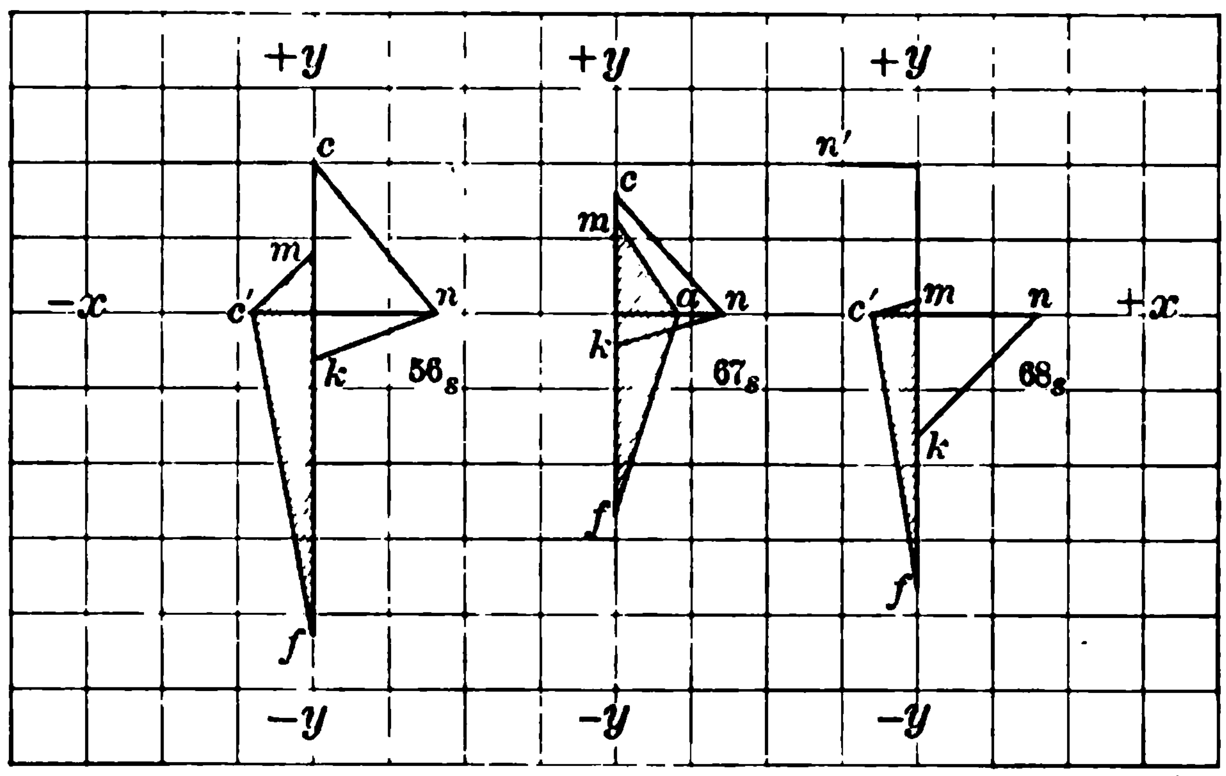



FIG. 6.

The component oxides are first distributed into two groups, those that may combine with $Al_2O_3$ to form feldspars, and those that may not. The plotting of the components will be understood from the following statement, *x* being the abscissas and *y* the ordinates, whose zero point is at the intersection of the two axes *x*, *y*:

− *y* . . . . . . *k*, potash involving an equal amount of alumina.
+ *x* . . . . . . *n*, soda which may be combined with the remaining alumina in equal amounts.
− *x* . . . . . . *n′*, soda which may be in excess of the available alumina.
(This is plotted as a line extending from the *y* axis, above the rest of the figure.)
+ *y* . . . . . . *c*, lime that may be combined with alumina in equal amounts after the alkalies are satisfied.
− *x* . . . . . . *c′*, lime in excess of that combined with alumina.
+ *y* . . . . . . *m*, magnesia.
− *y* . . . . . . *f*, iron oxide, both ferrous and ferric.
+ *x* . . . . . . *a*, alumina that may be in excess of that required to satisfy the alkalies and lime in *k*, *n*, and *c*.
*s*, silica, expressed by numerals at one side of the diagram.

The extremities of the lines *k* and *n* are connected by a straight line, also the extremities of *n* and *c*, of *f* and *c′*, *m* and *c′*, or of *a* and *f*, *a* and *m*.

[1] Michel-Lévy, A. Bull. Soc. géol., France, vol. 26, 1898, Pls. III to VI.
[2] Michel-Lévy, A. *Ibid.*, vol. 25, 1897, p. 344.

| | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$.... | 59.48 | 56.63 | 54.08 | 45.61 | 38.58 | 55.23 | 55.14 | 45.05 | 42.39 | 38.38 | 31.84 | 21.25 | 11.73 | 4.08 | 0.87 |
| | .991 | .944 | .901 | .760 | .643 | .921 | .919 | .751 | .707 | .640 | .531 | .354 | .196 | .068 | .014 |
| $Al_2O_3$... | 16.37 | 17.01 | 9.49 | 15.98 | 20.42 | 2.08 | 0.66 | 6.50 | 2.26 | 6.15 | 1.37 | 5.55 | 6.46 | 6.40 | 0.53 |
| | .160 | .164 | .093 | .156 | .200 | .021 | .005 | .064 | .022 | .060 | .014 | .054 | .063 | .063 | .005 |
| $Fe_2O_3$... | 3.21 | 6.15 | 3.19 | 8.25 | 7.60 | 3.94 | 3.48 | 3.83 | 0.35 | 11.70 | 15.63 | 43.45 | 30.68 | 33.43 | 87.60 |
| | .020 | .039 | .020 | .052 | .048 | .025 | .022 | .024 | .002 | .073 | .098 | .272 | .192 | .209 | .614 |
| FeO.... | 3.17 | 2.80 | 1.03 | 11.60 | 5.91 | 6.25 | 4.73 | 7.69 | 10.47 | 8.14 | 14.25 | | 27.92 | 34.58 | |
| | .044 | .039 | .014 | .161 | .082 | .087 | .065 | .107 | .146 | .113 | .199 | | .388 | .480 | |
| MgO.... | 3.29 | 4.08 | 6.74 | 3.75 | 12.93 | 29.29 | 26.66 | 12.07 | 39.19 | 11.47 | 33.10 | 18.30 | 3.35 | 3.89 | |
| | .082 | .102 | .169 | .094 | .323 | .732 | .667 | .302 | .980 | .287 | .827 | .458 | .084 | .097 | |
| CaO.... | 4.88 | 6.83 | 3.55 | 6.42 | 9.43 | 1.68 | 8.39 | 18.82 | 2.33 | 18.60 | 0.91 | 1.65 | 3.95 | 0.65 | |
| | .087 | .121 | .063 | .114 | .168 | .030 | .150 | .336 | .041 | .332 | .016 | .029 | .071 | .011 | |
| $Na_2O$... | 3.30 | 4.48 | 1.39 | 3.50 | 2.29 | | 0.30 | 0.94 | | 0.78 | | | 0.50 | 0.29 | |
| | .053 | .072 | .022 | .056 | .037 | | .005 | .015 | | .013 | | | .008 | .005 | |
| $K_2O$.... | 2.81 | 0.25 | 11.76 | 1.82 | 1.39 | | none | 0.78 | | 0.13 | | | 0.26 | 0.15 | |
| | .030 | .003 | .125 | .020 | .015 | | | .009 | | .001 | | | .003 | .002 | |
| $H_2O+$.. | 2.01 | 1.17 | 2.71. | 0.27 | 1.25 | 1.12 | 0.38 | 2.40 | 1.54 | 0.72 | 2.49 | 2.60 | 0.64 | 1.32 | |
| $H_2O-$.. | | | 0.79 | | | | | | | | | | | | |
| $TiO_2$.... | 0.93 | 0.18 | 2.08 | 1.15 | | 0.44 | tr. | 2.65 | | 4.32 | | 6.30 | 12.31 | 14.25 | 10.91 |
| | .012 | .002 | .026 | .014 | | .006 | | .033 | | 0.54 | | .079 | .154 | .176 | .137 |
| $P_2O_5$.... | 0.41 | 0.28 | 1.35 | 0.72 | | | 0.23 | 0.15 | | 0.17 | | 0.13 | 0.82 | 0.02 | |
| | .003 | .002 | .009 | .005 | | | .002 | .001 | | .001 | | .001 | .006 | | |
| Etc..... | 0.35 | 0.17 | 1.79 | 1.20 | | | 0.39 | | 0.28 | 0.16 | | 0.40 | 0.57 | 0.65 | |
| | 100.21 | 100.02 | 100.40 | 100.27 | 99.80 | 100.03 | 100.36 | 100.88 | 99.51 | 100.72 | 99.59 | 99.63 | 99.19 | 99.71 | 99.91 |

axes in one plane intersecting in a common zero point and making equal angles with one another, one being vertical, another horizontal, and the others at 45 degrees to these. The silica is represented by an octagon constructed by plotting one-eighth of the total silica plus and minus on each of the axes and connecting the extremities of these lines. The other components are plotted outside this area on particular axes by adding their values to that of the silica already plotted. The distribution of the several oxides is indicated by the symbols in Fig. 8. Alumina is divided into three

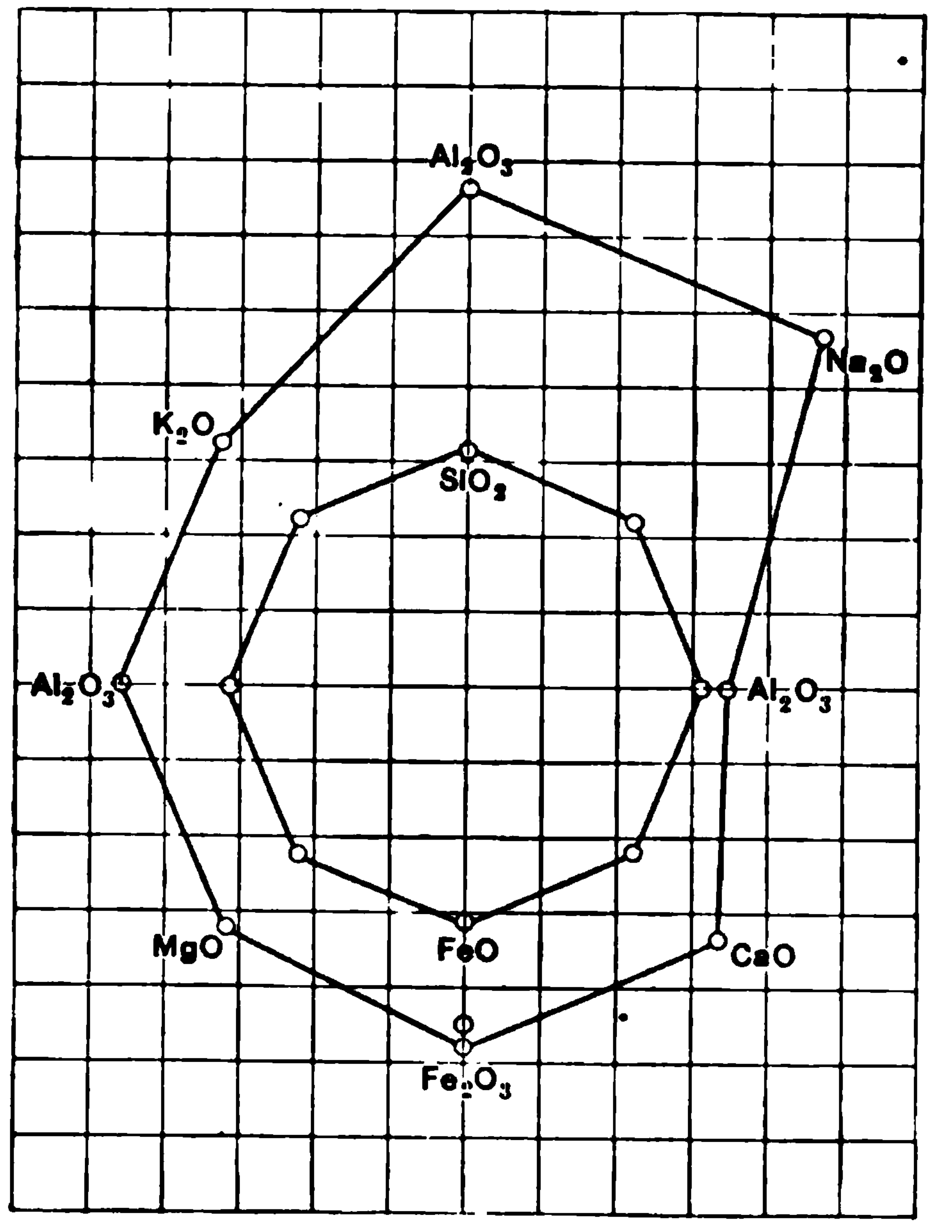



FIG. 8.

parts, when there is sufficient; one equal to $K_2O$ is plotted to the left on the horizontal axis; a second equal to $Na_2O$ is plotted upward on the vertical axis, and the remainder is plotted to the right on the horizontal axis. When there is less $Al_2O_3$ than $K_2O + Na_2O$, enough $Fe_2O_3$ is added to $Al_2O_3$ upward on the vertical axis to equal $Na_2O$. In this manner the relative amounts of potash-alumina molecules, soda-alumina molecules, and lime-alumina molecules are indicated.

**Fourth Type of Diagrams.** — In order to present the essential features of the data contained in all varieties of rock analyses the author has employed a compound diagram consisting of an assemblage of individual diagrams representing the relative molecular proportions of the principal chemical constituents in

nearly a thousand different rocks.[1] The individual diagram is a modification of those devised by Michel-Lévy and by Brögger. These are arranged in an orderly manner for comparison with one another. Plates I and II.

The small individual diagram exhibits the relative molecular amounts of the chief oxides in the analyses of igneous rocks: $Al_2O_3$, $Fe_2O_3 + FeO$, MgO, CaO, $Na_2O$, $K_2O$, and $TiO_2$; the silica being expressed by the position of the small diagram within the larger one. The comparison is made on a basis of the relative number of molecules rather than of percentage weights, because the molecule is the unit of comparison and of expression in the discussion of mineral compositions. It is readily found in any case by dividing the percentage weight of each oxide by its molecular weight. In the table of rock analyses already given the molecular proportions are stated for each oxide in addition to the percentage weights. The same is true for the rock analyses in the tables prepared by Washington.

For purposes of comparison in diagrams of this type it is not necessary to reduce the original analysis to a sum of exactly 100, for the diagrams are too small to permit the correction to be visible, and since the several elements in the diagram would be affected in like proportions, the shape and character of the diagram would not be appreciably affected.

The small individual diagram is constructed by plotting the molecular proportions of the components on coördinate axes that intersect at a common zero point, Fig. 9. For convenience in drawing on square-ruled paper, the axes are selected in vertical and horizontal positions, and at 45 degrees to these. The approximate relation between the sides and hypothenuse of a 45-degree right-angled triangle, namely, that when the hypothenuse is 10 units the sides are 7 units each (7.071), permits the values to be readily plotted. The mode of construction is as follows: $Al_2O_3$ is plotted vertically above the zero point; $K_2O$, upward to the left on one inclined axis; $Na_2O$, upward to the right on the other inclined axis; CaO is plotted downward on the vertical axis; MgO, downward to the right; $2\ Fe_2O_3 + FeO$, downward on the left; and $TiO_2$, when present in appreciable amount, is plotted to the left on the horizontal axis. The end of the

[1] Iddings, J. P. Prof. Paper, No. 18, U. S. Geological Survey, 1903.

$Al_2O_3$ ordinate is connected by lines with the ends of the $K_2O$ and $Na_2O$ ordinates; the end of the CaO ordinate is connected with the ends of the MgO and FeO ordinates. When $TiO_2$ is represented, the end of its ordinate is connected with that of the

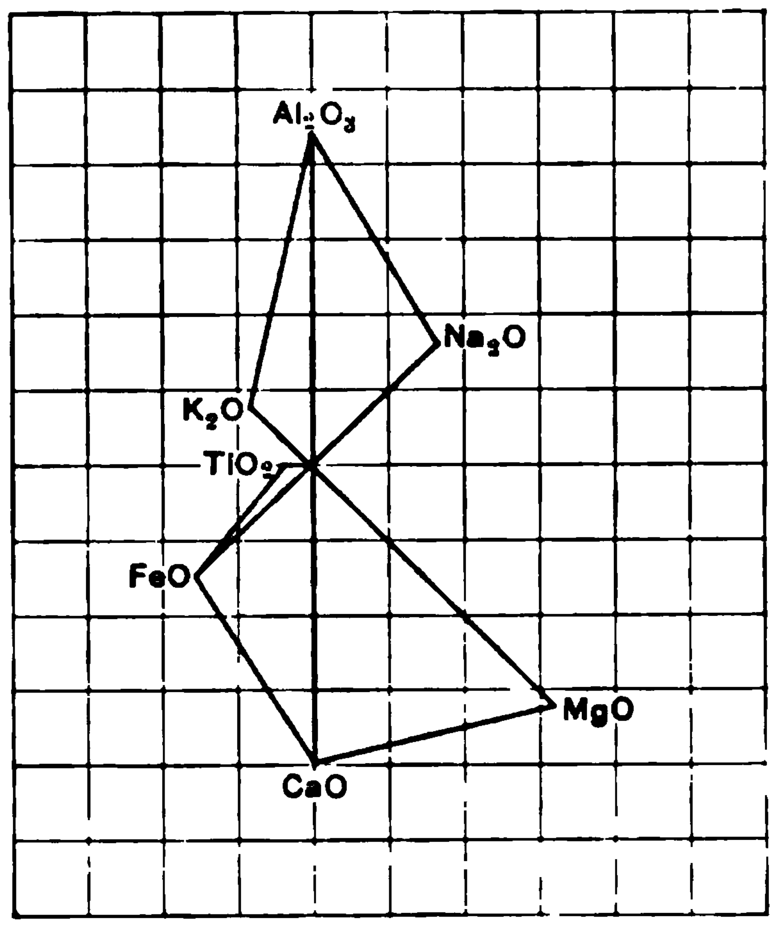



FIG. 9.

FeO ordinate. The FeO and $Fe_2O_3$ are combined after $Fe_2O_3$ has been reduced to FeO molecules by multiplying the number of $Fe_2O_3$ molecules by 2.

The two triangles on opposite sides of the vertical axes, having like angles of 45 degrees and a common side, have areas that are proportional to the coördinates on the inclined axes. That is, the areas of the two triangles on opposite sides of the $Al_2O_3$ ordinate are proportional to the ordinates $K_2O$ and $Na_2O$, and the areas of those on opposite sides of the CaO ordinate are proportional to the FeO + 2 $Fe_2O_3$ and MgO ordinates. So that the relative impressions produced by these pairs of triangles are quantitatively the same as the relations between the molecular proportions of $K_2O$ and $Na_2O$ on one hand, and of FeO + 2 $Fe_2O_3$ and MgO on the other.

As already stated, the $SiO_2$ is not expressed in the shape of the small individual diagram, but is indicated by the position of each small diagram in the large composite one. In this the horizontal axis is that of the $SiO_2$ with the zero point at the right, and

100 per cent at the left-hand end of the diagram. The percentage weights of $SiO_2$ are here used, as one object of the large diagram is to distribute the analyses with reference to silica so that those having like silica shall occur together, since silicon is the most abundant chemical element in most instances, and is a dominant factor in controlling the development of such minerals as quartz, orthoclase, albite, leucite, or nephelite, orthorhombic pyroxene, or olivine. But the vertical coördinates used in plotting the individual diagrams, indicating the alkalic character of the rock, represent ratios between the sum of the molecular proportions of the alkalies, $K_2O$ and $Na_2O$, and those of $SiO_2$. The alkalies were chosen as a second basis of comparison because of their important rôle in conditioning the character of the feldspathic minerals in rocks, and the fact that the lime, iron oxide and magnesia sustain to a considerable extent a reciprocal relation to the alkalies and silica, since the greater the silica and alkalies in general in a rock, the less the lime, magnesia and iron oxide.

## DIAGRAMS OF CHEMICAL ANALYSES OF IGNEOUS ROCKS

In the composite diagram, Plates I and II, 978 analyses of igneous rocks have been plotted. They represent all of the varieties of such rocks that had been analyzed at the time the diagram was constructed, 1902, but not all of the reliable analyses, for the reason that greater numbers of individual diagrams would have caused too great an overlapping of small figures. Those omitted occur in the central portion of the large diagram, which consequently does not strictly represent the proper proportions between the commoner and rarer varieties of rocks. This is shown more correctly in the diagram on Plate III, in which the black spots represent the loci of 2433 analyses plotted with reference to the silica and alkali-silica ratio in the same manner as that employed in locating the individual diagrams in the composite diagram on Plate I. A list of the analyses used in the diagram on Plates I and II is given in the paper on the chemical composition of Igneous Rocks already cited.[1] Those used in preparing the diagram on Plate III are the same as those

[1] Professional Paper, No. 18, U. S. Geological Survey, Washington, 1903, pp. 23–62.

in the previous plates with the addition of all other analyses contained in Part I of Washington's Tables, besides the "Superior Analyses of Igneous Rocks" from Roth's Tables,[1] and analyses from various other sources published since 1900.

A study of the small individual diagrams assembled on Plate I will convince one of the variability in the proportions of the chief chemical constituents in igneous rocks. No two analyses agree exactly in this respect. There is, however, a certain degree of order in the variations, which is shown by the similarity of neighboring diagrams, and by the fact that those near the left-hand end of the large diagram, and those near the upper limit of it, are characterized by relatively high alkalies and alumina, and low lime, iron and magnesia; while the diagrams near the lower limit of the large diagram exhibit the opposite relations. The distribution of different sorts of diagrams, however, is not in any simple manner, owing to the fact that there are more variables than can be referred to two coördinate axes.

Some general conclusions may be deduced from the diagram; among them the most obvious are: that the rocks with highest silica are lowest in all other constituents, which accords with the fact that igneous rocks grade into purely quartz rocks, as in certain pegmatites; the more siliceous rocks contain more alkalies and alumina than other constituents, which accords with the fact that the more quartzose rocks consist mostly of alkalic feldspars; furthermore, these rocks grade into others composed chiefly of alkalies and alumina with moderate to low silica, which correspond to rocks composed of alkalic feldspars alone or with nephelite and leucite. The limits of variation along these lines, the upper limits of the large diagram, are rocks composed wholly, or almost completely, of alkalic feldspars, and those wholly nephelite. A purely leucite rock has not yet been found. It is also evident from the diagram that rocks composed of any of the alkalic aluminous constituents just mentioned grade into others with increasing proportions of lime, magnesia and iron oxide until varieties are reached without alkalies or alumina, or with very small amounts of these constituents. Such rocks consist of pyroxene, alone or with olivine and mag-

[1] Washington, H. S., Professional Paper, No. 28, U. S. Geological Survey, 1904.

netite, or consist solely of olivine, or even of titaniferous magnetite. Rocks between these extremes are the vast majority, and consist of various minerals, among which lime-soda-feldspars are the most abundant, and form the limits of variations, which are not clearly indicated in the large diagram. Some of the extremes of variability, as well as the chemical average of all igneous rocks, are illustrated by the accompanying diagrams, Fig. 10, which represent eleven of the analyses given on pages 6 and 7. Other deductions which may be drawn from a consideration of these diagrams will be discussed in other connections.

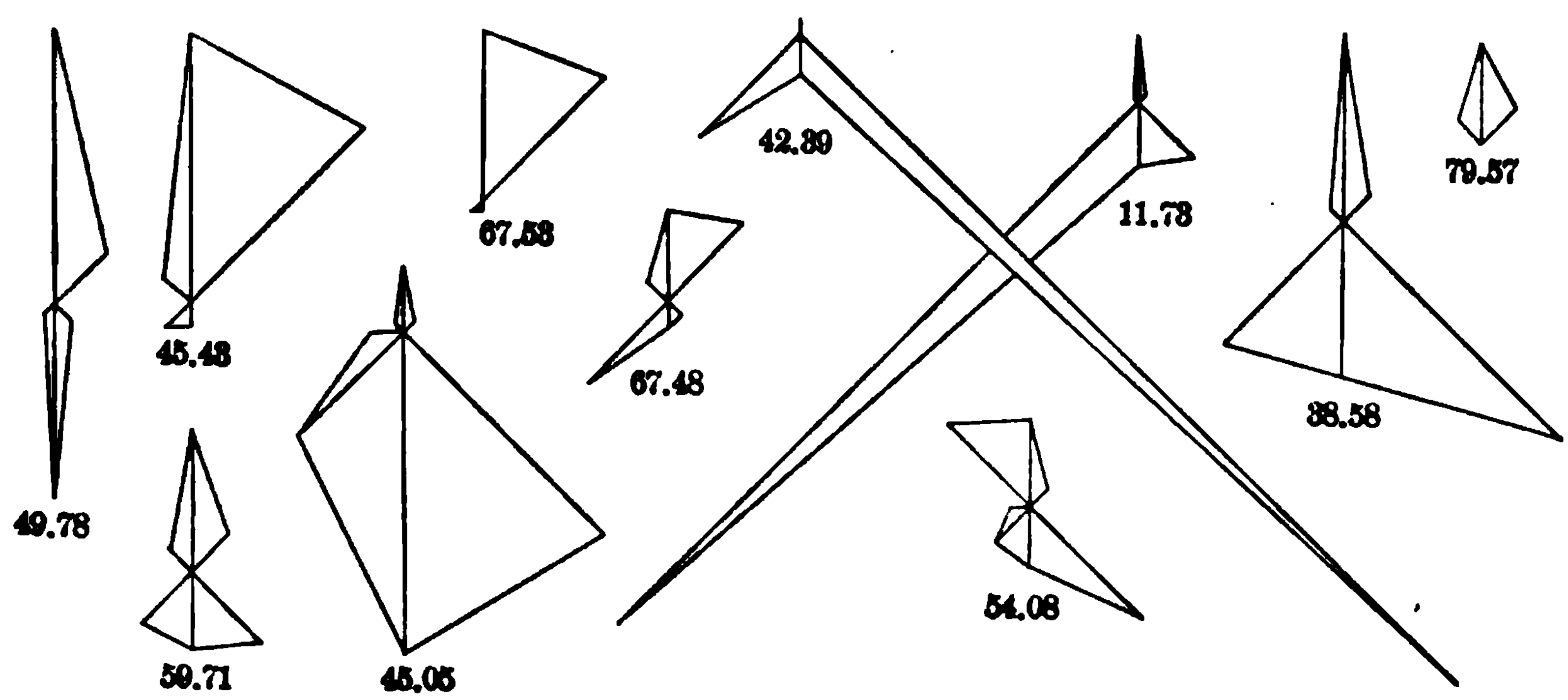



FIG. 10.

79.57, Alaskose (rhyolite), Montgomery Co., N. C., anal. 1,
67.53, Tuolumnose (albite-syenite), Tuolumne Co., Cal., anal. 3,
67.48, Pantellerose (pantellerite), Pantelleria, anal. 13,
59.71, Tonalose (average igneous rock), United States, anal. 15,
54.08, Orendose (orendite), Leucite Hills, Wyo., anal. 18,
49.78, Labradorose (anorthosite), Carlton Peak, Minn., anal. 7,
45.43, Urtose (urtite), Kola, Finland, anal. 8,
45.05, Brandbergose (pyroxenite), Brandberget, Norway, anal. 23,
42.39, Dunose (peridotite), Olivine Range, New Zealand, anal. 24,
38.58 (III, 6, 4, 3) (ariegite), Lherz, Pyrenees, France, anal. 20,
11.73, Adirondackiase (titaniferous iron ore), Essex Co., N. Y., anal. 28.

A study of Plate III shows the absence of clustering of spots or analyses in any manner that would suggest a grouping of rocks on a chemical basis into distinguishable classes or divisions. In other words, no "natural" classification of igneous rocks upon a chemical basis is indicated in the distribution of the spots

or analysis in the diagram with respect to silica and the alkalies. There is a general clustering of the majority of the spots or analyses in a broad belt extending horizontally through the lower middle of the large diagram on both sides of the location of the average of all rock analyses, or of the average rock, which spots are indicated by crosses, and occur at about 59.8 $SiO_2$ and 8.7. This corresponds to the fact that rocks of extreme chemical or mineralogical composition are rare, and that most igneous rocks are of intermediate composition with a considerable range of variability within more restricted limits than those of the extremes. The probable explanation of these facts will be considered in connection with a discussion of the origin of different kinds of igneous rocks and the possible causes of chemical variation among them, in Chapter VII.

Having called attention to the data concerning the chemical components of igneous rock, their chief repositories, and some of the methods by which they may be presented for investigation, the questions naturally arise: How are these chemical components or elements combined with one another in the rocks, and by what processes have they attained such combinations? The first of these questions will be answered in the following chapter on the chemical composition of the pyrogenetic minerals; the second will be considered in succeeding chapters, on the possible constitution of molten magmas or rock liquids, the chemical reactions capable of taking place within them, and their solidification into crystals or glasses.

# CHAPTER II

## CHEMICAL COMPOSITION OF THE PYROGENETIC MINERALS

In considering how the elements found in igneous rocks are combined with one another, it is to be noted that in a great number of cases such rocks are composed of crystals with definite chemical and physical characters, while some contain besides crystals more or less glass, whose composition is indefinite, which may be looked upon as a rigid solution of the rock constituents. The possible molecular character of such rigid solutions will be discussed in a subsequent chapter. The chemical character of the crystallized components of igneous rocks is the subject of the present one. The minerals here considered are those which have crystallized from the rock magma or liquid, the so-called pyrogenetic, or primary, ones, and do not include secondary minerals produced after the solidification of the magma by any processes of alteration or metamorphism. Since in some cases it is not yet demonstrable that a certain mineral was formed before, or after, the solidification of the magma, there may be found in the list of pyrogenetic minerals given below those about which there may be reasonable doubt. Moreover, there are minerals which may develop as pyrogenetic minerals, or as secondary ones, and also others concerning whose period of formation there are differences of opinion. It is to be remarked that pegmatite veins are considered to be intrusive igneous rocks; the reasons for this classification are to be found in Chapter VII.

In discussing the chemical composition of the pyrogenetic minerals, owing to the great number of them, the subject may be treated in various ways. And since it is desirable to present something more than a classified list of these minerals, it will be necessary to arrange them in groups that will set forth certain chemical facts and relationships. It is important also to note the particular compounds or minerals into which each element may enter, as well as the association of certain elements with one another. In the statement of these data, the compounds or minerals that are the most abundant, or the commonest, and those that are less abundant, but may be common,

are printed in the larger type, while those that are occasionally developed in considerable amounts, and those that are rare and seldom met with, are placed in the smaller type.

**Relative Proportions of the Chemical Elements in Igneous Rocks.** — A study of large collections of rock analyses shows that while there is a considerable range of variation in proportions, the components that are present in notable amounts are nearly the same in all cases, so that an average analysis of all that may be found in any large collection will present an approximation at least to the relative proportions in which the commoner and more abundant chemical elements occur in igneous rocks taken as a whole. Several estimates of such average analyses have been made from time to time by Clarke,[1] Harker,[2] and Washington.[3] The results agree closely, and we may take the latest,

| I. | | II. | | III. |
|---|---|---|---|---|
| | | O | 47.09 | 2.943 |
| $SiO_2$ | 59.87 | Si | 28.23 | .994 |
| $Al_2O_3$ | 15.02 | Al | 7.99 | .294 |
| $Fe_2O_3$ | 2.58 | Fe | 4.46 | .079 |
| FeO | 3.40 | .... | .... | .... |
| MgO | 4.06 | Mg | 2.46 | .101 |
| CaO | 4.79 | Ca | 3.43 | .085 |
| $Na_2O$ | 3.39 | Na | 2.53 | .109 |
| $K_2O$ | 2.93 | K | 2.44 | .062 |
| $H_2O-$ | .40 | H | .17 | .168 |
| $H_2O+$ | 1.46 | .... | .... | .... |
| $TiO_2$ | .72 | Ti | .43 | .009 |
| $ZrO_2$ | .03 | Zr | .026 | .000 |
| $CO_2$ | .52 | C | .14 | .011 |
| $P_2O_5$ | .26 | P | .11 | .003 |
| S | .11 | S | .11 | .003 |
| Cl | .07 | Cl | .07 | .002 |
| F | .02 | F | .02 | .001 |
| BaO | .11 | Ba | .089 | .000 |
| SrO | .04 | Sr | .034 | .000 |
| MnO | .10 | Mn | .084 | .001 |
| NiO | .03 | Ni | .023 | .000 |
| $Cr_2O_3$ | .05 | Cr | .034 | .000 |
| $V_2O_3$ | .03 | V | .02 | .000 |
| $Li_2O$ | .01 | Li | .01 | .001 |
| | 100.00 | | 100.000 | |

[1] Clarke, F. W. Bull. Phil. Soc., Washington, vol. 11, 1892, pp. 131–142. Also Bull. U. S. Geological Survey, No. 78, 1891, p. 34; *ibid.*, No. 148, 1897, p. 12; *ibid.*, No. 168, 1900, p. 14. Am. Phil. Soc., vol. 45, 1906, p. 20 of reprint. Also U. S. Geological Survey, Bull. 330, p. 26, 1908.

[2] Harker, A. Geol. Mag., vol. 36, 1899, p. 220.

[3] Washington, H. S., U. S. Geological Survey, Prof. Paper, No. 14, 1903, p. 108.

by Clarke, as sufficiently accurate for the present discussion. It is stated in column I. The percentage proportions of the atoms of the principal elements are given in II, from which the atomic proportions of these elements may be calculated and found to be as in III. The relative importance of these elements depends upon whether they are compared on a basis of atomic proportions or by percentage mass. It is to be observed that the percentage of $H_2O$ in the average rock is rather high for fresh unaltered rocks, and indicates that the rocks analyzed were not all perfectly fresh. It gives a somewhat erroneous impression of the hydrogen contained in the pyrogenetic minerals, but as there is an abundant escape of water in the form of vapor from all volcanic lavas at the time of their eruption, this emphasis of the hydrogen in the analyses offsets somewhat the actual loss of water at the time of solidification of the magma and may not overstate the composition of the liquid rock prior to eruption. The amount of carbon dioxide is excessive, and is chiefly of secondary origin and may be neglected. The succession in each case is as follows, beginning with the most abundant element: By atomic proportions, O, Si, Al, H, Na, Mg, Ca, Fe, K, Ti, P, S. By percentage mass, O, Si, Al, Fe, Ca, Na, Mg, K, Ti, H, P, S. It is seen that by either method of comparison, oxygen, silicon and aluminium are the most abundant elements, and in the order named. It may be concluded from this that all, or nearly all, of the compounds contain oxygen; and a very large part of them, silicon, while aluminium compounds must be very abundant.

At present there is no reliable means of estimating the relative proportions of the elements which occur in very small amounts.[1] Their occurrence in igneous rocks is variable, and their quantity is not always determined in rock analyses. Often their presence is not even indicated in the analysis, though it may be known from the occurrence in the rock of minerals containing them. These elements are Li (Cs), Gl, Sr, Ba, Ni, Co, B, Y, La, C, Zr, Th, Ge, Sn, Ce, etc., V, Cb, Ta, S, Cr, Mo, W, U, F, Cl; besides Au, and possibly Ag and Cu.

[1] Clarke, F. W. U. S. Geological Survey, Bull. 330, p. 26, Washington, 1908, and Vogt, J. H. L., Zeitschr. prakt. Geol., 1898, pp. 225, 314, 377, 413; 1899, pp. 10, 274. Kemp, J. F., Science, Jan. 5, 1906, Econ. Geol., vol. 1, p. 207, 1905. Washington, H. S., Trans. Am. Inst. Mining Eng., vol. 39, 1908, pp. 809–838. Also Hartley, W. N., and Ramage, H., Jour. Chem. Soc., vol. 71, p. 533, 1897.

**Possible Compounds.** — Anticipating the more thorough discussion of the chemical reactions within igneous rocks given in Chapter IV, in order to point out some of the essential relationships among the elements found in pyrogenetic minerals, a few of their simplest chemical characteristics will be stated here by way of introduction to the general discussion of the primary compounds found in these rocks.

Of the twelve elements first mentioned, O, Si, Al, Fe, Mg, Ca, Na, K, H, Ti, P, S, four, Si, Ti, P, and S, are capable of forming acids with hydroxyl (OH), while five, Fe, Mg, Ca, Na, and K, may form bases with OH. The elements Al and Fe may form bases or acids, being intermediate in their behavior between the pronounced basic and acid elements. They may be considered as weakly basic or acid, and may exist as oxides uncombined with other elements; especially is this true of Al. Similarly Si and Ti form rather weak acids, and may exist as oxides in the presence of the rather weak base-forming element Al. Moreover, it is known that Si is capable of forming several different silicic acids:

| | |
|---|---|
| $H_2Si_2O_5$ disilicic acid | $2\,(H_2O).4\,SiO_2$ |
| $H_4Si_3O_8$ polysilicic acid | $2\,(H_2O).3\,SiO_2$ |
| $H_2SiO_3$ metasilicic acid | $2\,(H_2O).2\,SiO_2$ |
| $H_4SiO_4$ orthosilicic acid | $2\,(H_2O).1\,SiO_2$ |

Furthermore, the stronger the base, the greater its tendency to combine with an acid, and, apparently, the higher the acid of a particular series with which it enters into combination. From the foregoing considerations it follows that the commoner, more abundant, elements in igneous rocks may be expected to combine with one another to form chiefly silicate minerals, together with small amounts of titanates or silicotitanates, since silicon and titanium are closely related to one another chemically, as indicated by their position in the Mendeléef series. There will also be very small amounts of phosphates, which may be expected to be stronger or more stable compounds than the silicates, since phosphorus is a stronger acid-forming element than silicon or titanium. Moreover the stronger base-forming elements probably will form higher silicates than the weaker base-forming elements, and will yield more stable compounds.

Considering the rarer elements found in igneous rocks, it is possible to predict the chemical nature of the less common pyrogenetic minerals. There must be silicates containing the rarer base-forming elements, Li, Cs,

Gl, Ba, Sr, Y, Ce, etc.; also those in which Si is replaced to a greater or less extent by Zr, Th. There must be those containing F, or Cl; and there may be fluorides and sulphides; also columbates and tantalates; molybdates, tungstates, uranates, etc.

## GENERAL DESCRIPTION OF PYROGENETIC COMPOUNDS ON A BASIS OF THEIR CHEMICAL CONSTITUENTS

**Mendeléeff's Law.** — In order to understand the method of arrangement and procedure in what follows, it is necessary to call attention to some of the well-known chemical characters and relationships that exist among the elements. When arranged in order of their atomic weight, they fall into a series in which elements having somewhat similar properties recur at regular intervals, according to what is known as Mendeléeff's law.[1] Some of these relationships are shown by the arrangement in the accompanying table, which, however, will not be described at length in this place. The elements occurring in igneous rocks constitute the greater part of those known, and occur throughout the series.

Among the base-forming elements those in the first subgroup of each group are generally the stronger. Among the acid-forming elements those of the second subgroup in each case are generally the stronger. But there is no constant rule, and the statement just made is not strictly true. Moreover, among the basic elements, those with heavier atomic weights usually form the stronger bases, whereas, among the acidic elements, those with lighter atomic weights usually form the stronger acids.

Elements belonging to the same subgroup frequently form isomorphous compounds, and may be found associated together in the same minerals. The same is true to some extent of elements belonging to the same group. But there are numerous compounds among the rock minerals that illustrate the dissimilarity of elements belonging to different subgroups of any one group. It is equally true that elements in one subgroup not infrequently exhibit marked differences of behavior, or in the character of analogous compounds, which will be noted in the discussion of the minerals which follows.

[1] See works on Chemistry, also F. P. Venable, Development of the Periodic Law, Easton, Penn., 1896; F. W. Clarke, U. S. Geol. Survey, Bull. 330, 1908, p. 35; J. P. Iddings, Rock Minerals, New York, 1906, p. 11; and T. Carnelly, Ber. deutsch. chem. Gesell., vol. 17, 1884, p. 2287.

PERIODIC ARRANGEMENT OF THE CHEMICAL ELEMENTS

| Series. | Group 0. | Group I. | Group II. | Group III. | Group IV. | Group V. | Group VI. | Group VII. | Group VIII. |
|---|---|---|---|---|---|---|---|---|---|
| | R | $R_2O$ | RO | $R_2O_3$ | $RH_4$ $RO_2$ | $RH_3$ $R_2O_5$ | $RH_2$ $RO_3$ | RH $R_2O_7$ | $RO_4$ |
| 1 | .......... | H=1 | .......... | .......... | .......... | .......... | .......... | .......... | .......... |
| 2 | He=4 | Li=7 | Gl=9.1 | B=11 | C=12 | N=14 | O=16 | F=19 | .......... |
| 3 | Ne=20 | Na=23 | Mg=24.4 | Al=27.1 | Si=28.4 | P=31 | S=32 | Cl=35.5 | |
| 4 | A=39.9 | K=39.1 | Ca=40.1 | Sc=44.1 | Ti=48.1 | V=51.2 | Cr=52.1 | Mn=55 | Fe=55.9, Ni=58.7 Co=59, Cu=63.6 |
| 5 | .......... | Cu=63.6 | Zn=65.4 | Ga=70 | Ge=72.5 | As=75 | Se=79.2 | Br=80 | |
| 6 | Kr=81.8 | Rb=85.5 | Sr=87.6 | Y=89 | Zr=90.6 | Cb=94 | Mo=96 | .......... | Ru=101.7, Rh=103 Pd=106.5, Ag=107.9 |
| 7 | .......... | Ag=107.9 | Cd=112.4 | In=115 | Sn=119 | Sb=120.2 | Te=127.6 | I=127 | |
| 8 | Xe=128 | Cs=132.9 | Ba=137.4 | La=138.9 | Ce=140.3 | .......... | .......... | .......... | .......... |
| 9 | .......... | .......... | .......... | .......... | .......... | .......... | .......... | .......... | |
| 10 | .......... | .......... | .......... | .......... | .......... | Ta=181 | W=184 | .......... | Os=191, Ir=193 Pt=194.8, Au=197.2 |
| 11 | .......... | Au=197.2 | Hg=200 | Tl=204.1 | Pb=206.9 | Bi=208 | .......... | .......... | .......... |
| 12 | .......... | .......... | Ra=225 | .......... | Th=232.5 | .......... | N=238.5 | .......... | .......... |

Thus it happens that some compounds, or minerals, have very simple and definite compositions, without mixture of elements which might be expected to be present, as $SiO_2$, $Al_2O_3$, $TiO_2$ and $ZrSiO_4$, while other compounds are highly complex, containing numerous elements, some closely related, others remotely so. It is possible also for several elements to enter into compounds in such a manner that their presence is difficult to express except by linking them together as radicals, such as (OH), (AlO), (MgF), etc. In such highly complex compounds as the tourmalines and amphiboles the physical properties of the crystals are considered to be controlled by the preponderant and invariable elements, which in the minerals mentioned form the acid radicals. This dominating and controlling action has been called *mass effect* by Penfield,[1] and has been referred by him especially to the acid radical.

Elements belonging to the same group are commonly associated together in rock magmas, and enter several different compounds or minerals within a given rock, so that certain rocks are characterized by the presence of minerals containing different amounts of several of the rarer elements. This is notably the case with the nephelite-syenite pegmatites of the Christiania region, and in some granitic pegmatites of other localities.

In the discussion that follows, the attempt is made to show in what compounds or minerals, and in what associations, the various elements are found in igneous rocks. The order followed is that in which the elements occur in groups in Mendeléeff's table.

## GROUP I

Cæsium, Rubidium, Potassium, Sodium, Lithium, univalent elements, capable of forming strong bases. Their activities vary in the order given, cæsium being the most active, lithium the least so. They fall into two subgroups; cæsium, rubidium and potassium being closely analogous in their chemical behavior. The compounds of sodium and lithium are somewhat different in some of their properties. Lithium forms insoluble carbonates and phosphates. As will be seen upon studying their occurrence in pyrogenetic minerals, potassium, sodium, and

[1] Penfield, S. L. Am. Jour. Sci., vol. 14, 1902, p. 211; *ibid.*, 23, 1907, p. 25.

lithium form like compounds and crystals in some cases, but not in others. Their modes of occurrence and frequency in igneous rocks are not always alike.

GOLD, SILVER, and COPPER have more than one valency, and are chemically quite distinct from the elements first named. They are seldom found in pyrogenetic minerals, and occur very rarely in the native, uncombined, state in igneous rocks. Copper is sometimes present as a sulphide. With this group is included hydrogen, though differing from the others in many respects.

**Cs, Rb. Cæsium** and **Rubidium** are extremely rare, and cæsium is a prominent constituent of only one pyrogenetic mineral, but with rubidium is associated in very small amounts with potassium and other elements of this group, sodium and lithium; occurring in several silicate minerals.

$H_2Cs_4Al_4(SiO_3)_9$. POLLUCITE. $H_2O \cdot 2Cs_2O \cdot 2Al_2O_3 \cdot 9\ SiO_2 = 40.7\ SiO_2$, 15.4 $Al_2O_3$, 42.5 $Cs_2O$, 1.4 $H_2O$ = 100. It contains small amounts of $Na_2O$, and less $K_2O$ and $Li_2O$. It is a metasilicate analogous to leucite, and occurs in granite. At Hebron, Me., it is found with quartz and a cæsium-beryl containing 3.6 $Cs_2O$. A cæsium-beryl also occurs at Norway, Me., with 1.66 $Cs_2O$. Pollucite occurs on Elba in granite with petalite (castorite). Traces of cæsium and rubidium are found in some leucite crystals, and notable amounts in lepidolite, that from Norway, Me., containing 3.73 $Rb_2O$.

**K. Potassium** is a common element in igneous rocks, and is a prominent constituent of some of the most abundant silicate minerals. It occurs in small amounts or in traces in others. Its chief occurrence is in aluminium silicates.

$KAlSi_3O_8$. ORTHOCLASE-MICROCLINE. $K_2O \cdot Al_2O_3 \cdot 6\ SiO_2 =$ 64.7 $SiO_2$, 18.4 $Al_2O_3$, 16.9 $K_2O$ = 100. A polysilicate in which sodium may be present in variable amounts. A compound isomorphous with albite, $NaAlSi_3O_8$.

This is the highest alumino-silicate of potassium formed by crystallization from igneous magmas, and occurs abundantly in the more quartzose rocks, granites, and in many rocks lower in silicon.

$KAl(SiO_3)_2$. LEUCITE. $K_2O \cdot Al_2O_3 \cdot 4\ SiO_2 = 55.0\ SiO_2$, 23.5 $Al_2O_3$, 21.5 $K_2O$ = 100. A metasilicate, containing a little sodium, and traces of cæsium and rubidium in some cases. It is abundant in certain igneous rocks, in which there is not sufficient silicon to make the polysilicate, orthoclase, and satisfy the other bases in the magma. It is not found in rocks containing pyrogenetic quartz.

$(K,H)Al(SiO_4)$. Muscovite, in part, also more siliceous, being mixtures of $H_2KAl_3(SiO_4)_3$ and $H_2KAl_3(Si_3O_8)_3$, when $2 H_2O \cdot K_2O \cdot 3 Al_2O_3 \cdot 6 SiO_2 = 45.2 SiO_2, 38.5 Al_2O_3, 11.8 K_2O, 4.5 H_2O = 100$. An acid orthosilicate of potassium and aluminium, in which there may be present small amounts of sodium, and traces of lithium, also fluorine. It may contain small amounts of iron and magnesium, being a very similar compound to biotite, which is distinctly ferromagnesian. Muscovite occurs in rocks rich in silicon and quartz, and also in those free from quartz and low in silicon, that is, in some granites and syenites and nephelite-syenites, but in those very low in iron and magnesium.

$(K,H)_2(Al,Fe)_2(SiO_4)_2(Mg,Fe)_2(SiO_4)$ and $(K,H)_2(Al,Fe)_2(SiO_4)_2(Mg,Fe)_4(SiO_4)_2$. Biotite. An orthosilicate like muscovite with part of the aluminium replaced by ferric iron, and with magnesium and iron in considerable amounts. There may be present also small amounts of titanium, fluorine, sodium, and lithium, also other elements. In one case 6.84 BaO, 0.47 SrO, Middletown, Conn. Biotite occurs in igneous rocks of widely different chemical composition, with, or without, quartz.

$K_2Na_6Al_8Si_9O_{34}$. Nephelite. When the ratio between K and Na is 1 : 3 the mineral contains 7.7 $K_2O$; usually there is from 4.5 to 5.5 $K_2O$. While potassium enters the composition of pyrogenetic nephelite, and there is a potassium aluminium orthosilicate, kaliophilite, isomorphous with sodium-nephelite, this potassium orthosilicate is not a primary constituent of igneous rocks, but occurs as a product of contact metamorphism, as when limestone is inclosed in the potassic lavas of Vesuvius.

Potassium is found in very small amounts and in traces in numerous silicate minerals containing sodium. There may be as much as one or two per cent of $K_2O$ in some tourmalines. It amounts to 5 per cent in the titanosilicate of iron and manganese, astrophyllite, a rare mineral. As compared with the wide-spread occurrence of sodium in pyrogenetic minerals potassium has a very limited range of occurrence, being found chiefly in potash-feldspar, leucite, muscovite and biotite, and also in nephelite.

**Na. Sodium** is the most abundant of the alkalic metals, being twice as great as potassium molecularly in the average igneous rock. Its chemical behavior is not strictly the same as that of potassium; it is known to form a weaker base than potassium, and its compounds are not always isomorphous with those of potassium, when analogous. That is, these elements are not

found replacing one another in all proportions in homogeneous crystals. Moreover, sodium is not so universally associated with aluminium in pyrogenetic minerals as is the case with potassium, and forms numerous compounds without aluminium, or with very small amounts of it. It occurs in a much greater number of different minerals than potassium.

$NaAlSi_3O_8$. ALBITE. $Na_2O \cdot Al_2O_3 \cdot 6\ SiO_2 = 68.7\ SiO_2$, 19.5 $Al_2O_3$, 11.8 $Na_2O$ = 100. A polysilicate in which a very small amount of sodium may be replaced by potassium. It is in a measure isomorphous with microcline, and is the highest silicate of sodium among the rock minerals. It occurs in highly siliceous rocks, with abundant quartz, and also in less siliceous ones with sufficient silicon. Owing to its strict isomorphism with anorthite, $CaAl_2Si_2O_8$, it crystallizes with this compound, when present, as lime-soda-feldspar, and as such is found in the vast majority of igneous rocks.

$NaAl(SiO_3)_2$. JADEITE. $Na_2O \cdot Al_2O_3 \cdot 4\ SiO_2 = 59.4\ SiO_2$, 25.2 $Al_2O_3$, 15.4 $Na_2O$ = 100. A metasilicate whose pyrogenetic character is not yet definitely determined, but its occurrence with albite and nephelite at one locality in Burma makes it seem probable that it is a pyrogenetic mineral. Its infrequent occurrence when compared with that of its potassium analogue, leucite, $KAl(SiO_3)_2$, is noteworthy, and emphasizes the lack of strict correspondence between these elements. The difference in crystal structure is also to be noted, jadeite being a monoclinic pyroxene. It may occur to some extent in isomorphous mixture with other pyroxene molecules.

$NaAl(SiO_3)_2 + H_2O$. ANALCITE. $Na_2O \cdot Al_2O_3 \cdot 4\ SiO_2 \cdot 2\ H_2O = 54.5\ SiO_2$, 23.2 $Al_2O_3$, 14.1 $Na_2O$, 8.2 $H_2O$ = 100. A hydrous metasilicate like leucite in crystal form. It is of rare occurrence as a pyrogenetic mineral, but is considered by some petrographers to be primary in a number of igneous rocks.

$K_2Na_6Al_8Si_9O_{34}$. NEPHELITE. $K_2O \cdot 3\ Na_2O \cdot 4\ Al_2O_3 \cdot 9\ SiO_2 =$ 44.0 $SiO_2$, 33.2 $Al_2O_3$, 15.1 $Na_2O$, 7.7 $K_2O$ = 100. An orthosilicate in which there are variable amounts of sodium and potassium, from $Na_2O:K_2O = 3:1$ to $5:1$. Owing to variations in the silica from that required to form orthosilicate, the percentage of silica increasing with the proportion of potash, it has been suggested that nephelite is a mixture of the sodium-aluminium-orthosilicate, $NaAl(SiO_4)$, which crystallizes in the laboratory like nephelite, and the metasilicate of potassium and aluminium, $KAl(SiO_3)_2$, which corresponds in composition to leucite. Nephe-

lite being a lower silicate than albite, occurs in igneous rocks low in silicon, in which there is not sufficient silicon to form albite and satisfy all the basic elements capable of forming silicates. Nephelite does not crystallize in magmas yielding primary quartz.

$H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$. Cancrinite. $3H_2O \cdot 4\ Na_2O \cdot CaO \cdot 4\ Al_2O_3 \cdot 9\ SiO_2 \cdot 2\ CO_2 = 38.7\ SiO_2$, 6.3 $CO_2$, 29.3 $Al_2O_3$, 4.0 CaO, 17.8 $Na_2O$, 3.9 $H_2O = 100$. An orthosilicate containing calcium and carbon which crystallizes from igneous magmas in company with nephelite, from which mineral it may in some cases be produced by alteration.

$Na_4(AlCl)Al_2(SiO_4)_3$. Sodalite. 37.2 $SiO_2$, 31.6 $Al_2O_3$, 25.6 $Na_2O$, 7.3 Cl = 101.7, less 1.7 O for Cl = 100. An orthosilicate of sodium and aluminium containing chlorine, which may be united with aluminium as the radical (AlCl); a small amount of potassium may replace sodium. For comparison with nephelite the formula may be written, $3(Na_2O \cdot Al_2O_3 \cdot 2\ SiO_2) + 2\ NaCl$. Sodalite crystallizes from the same kinds of rock magmas as nephelite, with which it is commonly associated.

$(Na_2,Ca)_2(NaSO_4 \cdot Al)Al_2(SiO_4)_3$. Haüynite. $Na_4(NaSO_4Al)Al_2(SiO_4)_3$. Noselite. Isomorphous orthosilicates containing sulphur and a variable amount of calcium. The more calcic compounds are called haüynite, the others are noselite. Potassium may be present in small amounts. When $Na_2O : CaO :: 3 : 2$, the composition of haüynite is 32.0 $SiO_2$, 14.2 $SO_3$, 27.2 $Al_2O_3$, 10.0 CaO, 16.6 $Na_2O$ = 100. For pure sodium-noselite, the composition is 31.7 $SiO_2$, 14.1 $SO_3$, 26.9 $Al_2O_3$, 27.3 $Na_2O$ = 100. For comparison with nephelite the formulas may be written:

Haüynite. — $3\,[(Na_2,Ca)O \cdot Al_2O_3 \cdot 2\ SiO_2] + 2\ Na_2SO_4$.
Noselite. — $3\,[Na_2O \cdot Al_2O_3 \cdot 2\ SiO_2] + 2\ Na_2SO_4$.

These orthosilicates crystallize from the same kinds of magmas as those in which nephelite and sodalite form, and are commonly associated with these minerals. They do not crystallize from magmas yielding primary quartz.

$Na\overset{III}{Fe}(SiO_3)_2$. Acmite. $Na_2O \cdot Fe_2O_3 \cdot 4\ SiO_2 = 52.0\ SiO_2$, 34.6 $Fe_2O_3$, 13.4 $Na_2O$ = 100. Metasilicate of sodium and ferric iron crystallizing as a monoclinic pyroxene, and isomorphous with the calcium, magnesium, iron proxenes, augite and diopside. It forms in magmas with insufficient aluminium to combine with the sodium present, as sodium-aluminium silicates. It occurs in

rocks high in silicon and also in those low in silicon, and may, or may not, be accompanied by quartz. When in isomorphous mixture with augite molecules the mineral is called ÆGIRITE-AUGITE.

$(Na\overset{III}{Fe})_2\overset{II}{Fe}(SiO_3)_5$. RIEBECKITE. $Na_2O \cdot FeO \cdot Fe_2O_3 \cdot 5\ SiO_2 =$ 50.5 $SiO_2$, 26.9 $Fe_2O_3$, 12.1 FeO, 10.5 $Na_2O$ = 100. A metasilicate similar to acmite with the addition of ferrous iron. It crystallizes as a monoclinic amphibole, and is isomorphous with other monoclinic amphiboles. It plays the same rôle among the amphiboles as acmite does among the pyroxenes, and crystallizes from similar magmas.

$(R,Na_2)SiO_3$. Sodium enters metasilicate compounds with other basic elements, Ca, Mg, Fe, Al, $\overset{III}{Fe}$, (K,H) in monoclinic amphiboles and to a less extent in pyroxenes, which, on account of their ability to replace one another in various proportions, have no fixed compositions, unless the ratio of calcium to the other components be taken into account. The following are some of the varieties:

$Na_8(Ca,Mg)_3(Fe,Mn)_{14}(Al,Fe)_2Si_{21}O_{45}$. ARFVEDSONITE, and a slightly more basic variety, BARKEVIKITE. Other varieties are KATOFORITE and HASTINGSITE. A somewhat analogous compound is ÆNIGMATITE or COSSYRITE, a triclinic amphibole of rare occurrence, containing a notable amount of titanium.[1]

$Na_{13}(Ca,Fe)_6Cl(Si,Zr)_{20}O_{52}$. EUDIALYTE (eucolite), essentially a metasilicate, $\overset{I}{R}_4\overset{II}{R}_3Zr(SiO_3)_7$, with $\overset{I}{R}$ chiefly Na, also K, H; $\overset{II}{R}$ chiefly Ca, also Fe, Mn, and Ce (OH); and with $ZrOCl_2$ in part replacing $SiO_2$; columbium (tantalum) may be present in small amounts. Contains from 10 to 13 per cent of $Na_2O$. Occurs with nephelite, sodalite, and other sodic minerals.

$H_2(Na_2,Ca)(Zr(OH)_2)(SiO_3)_3$. CATAPLEIITE. When free from calcium its composition is 46.1 $SiO_2$, 28.8 $ZrO_2$, 15.9 $Na_2O$, 9.2 $H_2O$ = 100. It is a rare mineral associated with zircon and with various sodic minerals in the nephelite-syenite-pegmatites of the Christiania Fjord, Norway.

$Na(GlF)Ca(SiO_3)_2$. LEUCOPHANITE. 49.4 $SiO_2$, 10.3 GlO, 23.0 CaO, 12.8 $Na_2O$, 7.9 F = 103.4, less 3.4 O for F = 100. A rare mineral in the nephelite-syenite-pegmatites of the Christiania Fjord.

$NaCa_2Gl_2FSi_3O_{10}$. MELIPHANITE. 46.9 $SiO_2$, 13.1 GlO, 29.1 CaO, 8.1 $Na_2O$,

[1] For analyses of these amphiboles, see Rock Minerals, p. 339. For a discussion "of the chemical composition of amphibole," by S. L. Penfield and F. C. Stanley, see Am. Jour. Sci., vol. 23, 1907, pp. 23–51.

5.0 F = 102.2, less 2.2 O for F = 100. Very similar to leucophanite in composition and mode of occurrence.

Sodium occurs in small amounts in the pyrogenetic micas, but the sodium-mica, paragonite, is not a pyrogenetic mineral. Sodium also occurs in small amounts in tourmaline, there being as much as 3.0 $Na_2O$ in some varieties. It is present in very small amounts in the minerals of the melanocerite group.

In certain pyrogenetic titanosilicates sodium is present in amounts as follows: 2.0 to 4.0 per cent in astrophyllite; 6.67 in johnstrupite; 2.44 in mosandrite; 8.98 in rinkite. There is in the columbate, pyrochlore, 5.0, $Na_2O$.

$NaGlPO_4$. Beryllonite. $Na_2O \cdot 2\ GlO \cdot P_2O_5$ = 55.9 $P_2O_5$, 19.7 GlO, 24.4 $Na_2O$. A phosphate of sodium and glucinum occurring with beryl, columbite, quartz, and feldspars in a granite pegmatite at Stoneham, Me.

**Li. Lithium**, which forms the weakest base of the alkalic elements, has certain similarities to potassium, and others nearer to sodium. It is found in traces in numerous igneous rocks, and in notable amounts in the more quartzose rocks rich in alkalies and aluminium, certain granites. It is a prominent component of some quartzose pegmatites. It forms several aluminous silicates as follows:

$LiAl(Si_2O_5)_2$. Petalite. $Li_2O \cdot Al_2O_3 \cdot 8\ SiO_2$ = 78.4 $SiO_2$, 16.7 $Al_2O_3$, 4.9 $Li_2O_3$. It contains small amounts of $Na_2O$ and traces of $K_2O$. A disilicate, the most siliceous mineral. It is a rare mineral, somewhat like pyroxene, spodumene, and occurs in granitic pegmatite with other lithium minerals, thus at Peru, Me., with spodumene, albite, beryl, triphylite; at Utö, Sweden, with magnetite, spodumene, lepidolite, tourmaline, and quartz; at Elba, in granite with orthoclase, albite, lepidolite, tourmaline, garnet, cassiterite, beryl, pollucite, and quartz.

$LiAl(SiO_3)_2$. Spodumene. $Li_2O \cdot Al_2O_3 \cdot 4\ SiO_2$ = 64.5 $SiO_2$, 27.4 $Al_2O_3$, 8.4 $Li_2O$. A metasilicate generally containing small amounts of sodium. A pyroxene-like mineral occurring in granitic pegmatites associated with other lithium minerals, both silicates and phosphates, lepidolite, petalite, amblygonite, lithiophilite, triphylite, and other minerals. Prominent localities are Branchville, Conn.; Huntington, Mass.; Killiney Bay, near Dublin; Peterhead, Scotland; Utö, Sweden.

It is interesting to note that spodumene at Branchville, Conn., alters to albite and the lithium aluminium orthosilicate, eucryptite, as lithium-nephelite, $LiAlSiO_4$, which, however, is not known as a primary, pyrogenetic mineral.

$HKLiAl_3(SiO_4)_3$ and $K_3Li_3(AlF_2)_3Al(Si_3O_8)_3$. LEPIDOLITE. Lithium mica containing sometimes small amounts of rubidium and cæsium. 49.62 $SiO_2$, 27.30 $Al_2O_3$, 0.31 $Fe_2O_3$, 0.07 FeO, 0.55 MnO, 8.03 $K_2O$, 4.34 $Li_2O$, 2.17 $Na_2O$, 2.44 $Rb_2O$, 0.72 $Cs_2O$, 1.52 $H_2O$, 5.45 F = 102.52, Auburn, Me. It occurs in granite and granitic pegmatite with spodumene, amblygonite, tourmaline, etc., and is often associated with potash-mica, muscovite, in parallel growth.

$H_2K_4Li_4Fe_3Al_8F_8Si_{14}O_{42}$. ZINNWALDITE. Lithium-iron-mica. Other varieties with slightly different proportions are CRYOPHYLLITE from Cape Ann, Mass., and POLYLITHIONITE from Kângerdluarsuk. Composition near that of lepidolite with part of the alumina replaced by iron oxide. Polylithionite contains almost no iron, and 7.63 $Na_2O$. It occurs in granite at various localities, and in association with cassiterite at Zinnwald, and in Cornwall.

In TOURMALINE lithium sometimes occurs in small amounts together with sodium and a little potassium. It is found in traces in other alkali-bearing silicates.

$Li(Fe,Mn)PO_4$. TRIPHYLITE and LITHIOPHILITE. Phosphates of lithium with iron and manganese in varying proportions, having 9.5 $Li_2O$. Typical triphylite is $LiFePO_4$, 45.0 $P_2O_5$, 45.5 FeO, 9.5 $Li_2O$. Typical lithiophilite is $LiMnPO_4$. 45.3 $P_2O_5$, 45.1 MnO, 9.6 $Li_2O$. These minerals occur with spodumene in granite pegmatites.

$Li(AlF)PO_4$. AMBLYGONITE. A fluophosphate of lithium and aluminium 47.9 $P_2O_5$, 34.4 $Al_2O_3$, 10.1 $Li_2O$, 12.9 F = 105.3 less 5.3 O for F = 100. Sodium may replace part of the lithium, and hydroxyl part of the fluorine. It occurs with other lithium minerals in granite pegmatites in several localities in Maine, at Branchville, Conn., and elsewhere.

H. **Hydrogen** enters into the composition of various pyrogenetic minerals to a greater or less extent, and is generally grouped with the base-forming elements. It is undoubtedly more abundant in liquid magmas than in solidified rocks, as is indicated by the great volume of water vapor and some hydrogen gas, and other hydrogen-bearing gases, that escapes from lavas at the time of volcanic eruptions.

$H_2O$. WATER is present as primary inclusions in some pyrogenetic minerals, especially in quartz. It probably exists to a very small amount in numerous minerals in solid solution.

H or (OH). Hydrogen or hydroxyl enters the composition of numerous pyrogenetic silicates, and the percentages of $H_2O$ in various minerals are as follows: 5 to 6 in muscovite; 1 to 2 in lepidolite; 2 to 4 in biotite; there is a variable small amount in amphiboles; about 5 in allanite; about 2 in epidote; about 4 in cancrinite; from 1 to 4 in tourmaline; 8.2 in analcite·

9.2 in catapleiite; 3 in melanocerite; 4.8 in caryocerite; 6.5 in tritomite; 1.5 in cordierite; 2.4 in pollucite. In the titanosilicates: 4.8 in astrophyllite; 10.25 in mosandrite; 1.8 in johnstrupite. In the columbates and tantalates: 5 in hatchattolite; 6.7 in yttrotantalite, etc. In the phosphates: 3.7 in herdrite; 4.1 in triploidite; and 6.6 in amblygonite.

**Au.** Gold uncombined with other elements is rare as a pyrogenetic mineral. It has been found in granite from Sonora, and in pitchstone from Chili.

**Cu.** Çopper in an uncombined form is frequently associated with basaltic rocks in such a manner as to appear to be genetically related to them.

$CuFeS_2$. CHALCOPYRITE. Sulphide of copper and iron, 34.5 Cu, 30.5 Fe, 35.0 S = 100. Occurs with pyrrhotite and pentlandite in certain igneous rocks rich in ferromagnesian silicates, gabbro, in Canada and Norway. Copper also occurs in small amounts in some pyrogenetic pyrite.

## SUMMARY FOR GROUP I

The heaviest elements of this group, Cs and Rb, are extremely rare, and are associated with the other members of the group, especially K and Li, and like them occur chiefly in silicates, with aluminium, and in one compound, with glucinum (beryllium).

Potassium, the most active of the common elements of this group, is almost wholly confined to silicate compounds containing aluminium, and is only combined with magnesium and iron to some extent in mica, biotite. It does not combine to any considerable extent with calcium in pyrogenetic minerals. It does not form normal orthosilicate compounds, but is common in an acid orthosilicate, muscovite, and biotite which may crystallize with quartz. The common normal salts are polysilicate, orthoclase-microcline, and metasilicate, leucite.

Sodium, a less active element than potassium, is more abundant in igneous rocks, and enters a greater variety of compounds. It resembles potassium in its tendency to form aluminous silicates, but differs from it in frequently entering non-aluminous silicates, and in forming isomorphous mixtures with calcium silicates. It also combines with glucinum in a phosphate, which is, however, a very rare mineral. Sodium differs from potassium in not forming a pyrogenetic mica, and in frequently crystallizing as normal orthosilicates, and very rarely as a metasilicate compound analogous to leucite.

Lithium, the least active element of this group, resembles potassium in forming in most cases aluminous silicates, especially occurring in a mica associated with muscovite and biotite. How-

ever, it is similar to sodium in that its aluminous metasilicate is a pyroxene-like mineral, similar to jadeite. It also occurs as phosphates, but with aluminium, or iron and manganese.

Lithium, with the rarer elements cæsium and rubidium, occurs chiefly in the more siliceous magmas, the resulting minerals being constituents of granites and granitic pegmatites. Potassium also is more common in the more siliceous rocks than in the less siliceous ones; while sodium has a wider range, and is a notable constituent of many rocks low in silica. It is also very abundant in the more siliceous rocks.

Hydrogen, which differs greatly in many of its characters from other univalent elements, enters a number of pyrogenetic minerals.

Gold occurs very rarely, and in the more siliceous rocks, while copper, both native and as sulphide, is of more frequent occurrence, and is found in the less siliceous rocks.

### GROUP II

Barium, Strontium, and Calcium, possibly Radium, are bivalent elements capable of forming bases not so strong as those of Group I. Of these, calcium alone is common as a constituent of pyrogenetic minerals. Compounds of these elements have in certain cases resemblances with some of those belonging to Group I. In such cases barium may enter isomorphously compounds with potassium, while calcium may enter those with sodium oftener than those with potassium.

Mercury and Cadmium have not been noted among pyrogenetic compounds; Zinc is extremely rare; Magnesium is very abundant; Glucinum is among the rarer elements. Bivalent Iron with Manganese, Nickel, and Cobalt are to be classed with elements in this group, and have their closest analogies with magnesium. Magnesium, glucinum, and zinc are bivalent in all their compounds; the others just mentioned have different valencies. Magnesium always plays the rôle of a base; it never enters the acid radical. Glucinum is in some compounds basic, but is acidic in its behavior towards strongly basic elements. Iron in ferrous and ferric oxides and hydroxides is basic, the ferrous compounds more strongly so than the ferric, which may also be acidic, and furnish ferrates. The same is true of cobalt, but there are no

nickelic salts; nickel is otherwise similar to iron and cobalt. Bivalent manganese resembles iron in that MnO is always basic, while $Mn_2O_3$ is in some cases feebly basic, in others feebly acidic.

Magnesium, iron, and manganese replace each other isomorphously in numerous pyrogenetic compounds. Cobalt and nickel may enter the same compounds isomorphously, but are rare elements in pyrogenetic minerals. Salts of these elements are slightly hydrolyzed by water.

Glucinum is rather independent of other elements of this group in its occurrence, but is sometimes associated with calcium, iron, manganese, and zinc in pyrogenetic minerals.

**Ba, Sr. Barium and Strontium** are extremely rare elements in igneous rocks, and do not characterize any pyrogenetic mineral. They occur in traces in several silicates, being sometimes noted in feldspar, especially potash-feldspar, isomorphous with which there is the barium compound, celsian, found in metamorphic rocks. Hyalophane is an intermediate mixture of the two. There is 8.29 BaO in cappelenite, $RSiO_3 \cdot YBO_3$, a borosilicate of yttrium and barium, occurring in very small amounts in nephelite-syenite on Lille Arö, Norway.

**Ca. Calcium** is one of the most abundant and wide-spread elements in igneous rocks, and enters a great variety of compounds, the commonest of which are silicates. But there are also calcium-bearing phosphates, titanates, and columbates, among the less abundant minerals.

$CaAl_2(SiO_4)_2$. ANORTHITE. CaO, $Al_2O_3$, 2 $SiO_2$ = 43.2 $SiO_2$, 36.7 $Al_2O_3$, 20.1 CaO = 100. Orthosilicate of calcium and aluminium, or possibly an aluminosilicate of calcium and aluminium, $CaAlAlSi_2O_8$. A compound isomorphous with albite and crystallizing with it in all proportions in the lime-soda-feldspars. The combination of aluminium with calcium is not so strong as that between potassium, or sodium, and aluminium, for it does not form to any considerable extent when there is potassium or sodium in the magma uncombined with aluminium. The anorthite compound in combination with albite crystallizes from magmas with quartz as well as from less siliceous magmas. But it is much more common in the less siliceous rocks.

Ca(Mg,Fe) $(SiO_3)_2$, or $CaR(SiO_3)_2$. DIOPSIDE-AUGITE. Calcium enters a metasilicate compound with magnesium, iron, and subordinate amounts of aluminium, ferric iron, and sodium, which may

probably be represented by R in the second formula, the proportion between the calcium and the other basic elements being that of 1:1 approximately. In diopside and augite there is commonly from 20 to 26 per cent CaO.

$CaR(SiO_3)_2$, $Na\overset{III}{Fe}(SiO_3)_2$. ÆGIRITE-AUGITE. In this mineral, CaO varies from 20 to 2 per cent, and is absent from pure acmite, the extremely sodic member of the isomorphous series of pyroxene compounds.

$CaR_3(SiO_3)_4$. AMPHIBOLE. Calcium forms a metasilicate with magnesium, iron, aluminium, sodium, and traces of other allied elements, and with radicals containing hydrogen and fluorine, somewhat analogous to the pyroxene compounds, but with a different ratio between the calcium and the other basic elements and radicals. In amphiboles it is approximately 1:3, so that the amphiboles are distinctly less calcic compounds than the calcic pyroxenes. In common hornblende there is from 10 to 14 per cent of CaO. In the more sodic varieties the CaO decreases to 5 and 1.5 per cent. Thus it is seen that there is about half as much calcium in amphiboles as in the corresponding pyroxenes.

$12\,(Ca, Na_2) \cdot (Si,Zr)O_3 \cdot RCb_2O_6$ with F. WÖHLERITE. Zirconosilicate of calcium and sodium with small amounts of other bases and a notable amount of columbium. It contains about 27.0 CaO, and occurs in nephelite-syenite pegmatite in Norway.

$Ca_3Na_2((Si,Zr,Ti)O_3)_4$. ROSENBUSCHITE. Zirconosilicate of calcium and sodium, with titanium and fluorine. It carries about 25.0 CaO, and occurs associated with wöhlerite in Norway, and in similar rocks in Brazil and in North America.

$Na(Mn,Ca,Fe)(ZrO,F)(SiO_3)_2$. LÅVENITE. Zirconosilicate of sodium, calcium, manganese, and iron, with basic zirconium, besides fluorine, titanium, columbium, and tantalum. It contains about 7.0 CaO and is crystallized in nephelite-syenite pegmatites in Norway and elsewhere, as well as in certain porphyritic and lava forms of similar magmas.

$Na_{13}(Ca,Fe)_6Cl(Si,Zr)_{20}O_{52}$ or $\overset{I}{R}_4\overset{II}{R}_3Zr(SiO_3)_7$. EUDIALYTE (eucolite). A metasilicate of sodium and calcium, with zirconium, iron, cerium, tantalum, and other elements; CaO from 10 to 14 per cent; occurring in nephelite-syenite rocks.

$H_2(Na_2,Ca)(Zr(OH)_2)(SiO_3)_3$. CATAPLEIITE. A metasilicate of sodium, calcium, with hydrogen and zirconium, which may contain variable amounts of calcium up to 5.82 per cent; occurs in nephelite-syenite pegmatites in Norway.

$NaCa(GlF)(SiO_3)_2$. LEUCOPHANITE. 49.4 $SiO_2$, 10.3 GlO, 23.0 CaO, 12.8 $Na_2O$, 7.9 F = 103.4 less 3.4 O for F = 100. And the following mineral.

$Na_2(GlF)_2(Ca_2O)_2Gl_2(SiO_3)_6$. MELIPHANITE. 46.9 $SiO_2$, 13.1 GlO, 29.1 CaO, 8.1 $Na_2O$, 5.0 F = 102.2 less 2.2 O for F = 100. These compounds containing notable amounts of calcium crystallize from nephelite-syenite-pegmatite magmas in Norway.

$(Ca,Fe)_3(BO)_2(SiO_4)_2$. HOMILITE. 2 CaO · FeO · $B_2O_3$ · 2 $SiO_2$ = 32.1 $SiO_2$, 18.7 $B_2O_3$, 19.3 FeO, 29.9 CaO = 100. A rare orthosilicate occurring intimately associated with meliphanite in nephelite-syenite pegmatite in Norway.

Calcium occurs in small amount in the rare silicate minerals melanocerite, caryocerite, and tritomite, which are characterized chiefly by the presence of the rare elements, Ce, La, Di, Y, Th, B, and occur in the nephelite-syenite pegmatites in Norway. Calcium also occurs in the somewhat similar compound beckelite formed in nephelite-syenite in Russia (?).

$(Ca,Mg,Fe)_3((Al,Fe)O)_2SiO_4$, or $(Ca,Mg)_4Si_3O_{10}$ (?). MELILITE. A silicate of doubtful composition owing to discordant analyses. There may be some sodium and a little potassium present. CaO = 27.47 to 32.47 per cent. Melilite occurs in igneous rocks low in silicon, in which there is not sufficient silicon to form the commoner pyrogenetic silicates.

$(Ca,Mg,Fe)_3(Al,Fe)_2(SiO_4)_3$. GARNET. Calcium combined with magnesium, iron, and aluminium in an orthosilicate. The proportions of the different elements entering the isomorphous mixture in any particular case depend, to a considerable extent, on the chemical composition of the rock magma. In most cases calcium is subordinate to the other elements in pyrogenetic garnets, the distinctly calcium garnets being mostly metamorphic minerals. Garnets, though orthosilicates, crystallize from igneous magmas with quartz, as well as from those without quartz.

$Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$. EPIDOTE. A basic orthosilicate of calcium and aluminium with variable amounts of iron. The percentage of CaO varies from 20.7 to 24.6. Though mostly a secondary mineral epidote is sometimes a pyrogenetic one, having crystallized from the magmas of certain granites, and therefore with quartz. Its occurrence in these rocks is analogous to that of:

$(Ca,Fe)_2(AlOH)(Al,Ce,Fe)_2(SiO_4)_3$. ALLANITE, cerium-epidote, a pyrogenetic mineral in which calcium is present in variable proportions: CaO = 17.37 to 1.40 per cent.

$\begin{bmatrix} F_6\overset{IV}{R}_3 \\ F\overset{III}{R} \end{bmatrix}(\overset{I}{R}_2)_4\overset{II}{R}_{13}\overset{III}{R}_2(SiO_4)_{12}$. JOHNSTRUPITE, MOSANDRITE, RINKITE. Complex silicates of calcium, sodium, and the cerium metals, with titanium and fluorine, having CaO from 22.53 to 27.76 per cent. Rare minerals crystallizing in nephelite-syenite pegmatites; the first two varieties in Norway; the third, rinkite, in Greenland and at Serra de Tingua, Brazil.

$CaSiTiO_5$. TITANITE. $CaO \cdot TiO_2 \cdot SiO_2 = 30.6\ SiO_2$, $40.8\ TiO_2$, $28.6\ CaO = 100$. A titanosilicate of calcium of widespread occurrence in igneous rocks, chiefly the more siliceous kinds. It is not commonly developed in the less siliceous varieties. An orthorhombic mineral, *guarinite*, having the same composition as titanite, occurs in lava on Monte Somma.

$15\ CaTiSiO_5 \cdot (Al,Fe,Y)_2(Si,Ti)O_5$. KEILHAUITE. A titanosilicate of calcium, aluminium, ferric iron and the yttrium metals, with from 17.15 to 25.03 CaO. Occurs in a feldspathic rock, (?) syenite, at Arendal, Norway.

$CaTiO_3$. PEROVSKITE. $CaO \cdot TiO_2 = 58.9\ TiO_2$, $41.1\ CaO = 100$. Calcium titanate crystallizing in magmas so low in silicon that the titanosilicate, titanite, does not form.

$RCb_2O_6 \cdot R(Ti,Th)O_3 \cdot NaF$. PYROCHLORE. A columbate of the cerium metals, calcium, and other bases, with titanium, thorium, and fluorine; CaO from 11 to 16 per cent; a rare mineral occurring in nephelite-syenite, syenite and alkalic granite in several localities.

Calcium also occurs in other rare columbates and tantalates such as microlite, hatchettolite, fergusonite, sipylite, and others.

$(Ca(F,Cl))Ca_4(PO_4)_3$. APATITE. $(3\ CaO \cdot P_2O_5)_3 + Ca(F,Cl)_2$. For fluor-apatite $42.3\ P_2O_5$, 55.5 CaO, 3.8 F = 101.6; chlor-apatite $41.0\ P_2O_5$, 53.8 CaO, 6.8 Cl = 101.6. There may be also (OH), Mn, and rarely Di, Ce, La. Apatite is a common constituent of nearly all igneous rocks, but usually occurs in very small amount, being more abundant in the less siliceous and less feldspathic rocks.

Calcium also occurs in the rare pyrogenetic phosphates: herderite, (CaF) $GlPO_4$, with 34.6 CaO; and triplite, $(RF)RPO_4$, with 2.0 to 6.0 CaO.

$CaWO_4$. SCHEELITE. $CaO \cdot WO_3 = 80.6\ WO_3$, 19.4 CaO = 100. Usually some molybdenum is present replacing tungsten. This rare mineral is found in association with granitic rocks in such a manner as to be probably pyrogenetic. Thus at Chesterfield, Mass., it occurs with albite and tourmaline.

$CaCO_3$. CALCITE. $CaO \cdot CO_2 = 56.0\ CaO$, $44.0\ CO_2 = 100$. Variable amounts of magnesium and iron may be present. Calcite is considered by some petrographers as a pyrogenetic mineral in certain igneous rocks, where its presence may be the result of absorption from carbonate rocks near their contact with igneous magmas. It is commonly a secondary mineral.

$CaF_2$. FLUORITE. Calcium fluoride 51.1 Ca, 48.9 F = 100; of widespread occurrence in small amounts in different kinds of igneous rocks.

**Mg. Magnesium,** though closely allied to calcium in some respects, differs from it notably in the manner in which it forms compounds. It occurs frequently in compounds without calcium, is absent from many containing calcium, and when it enters calcium-bearing compounds, it is not strictly isomorphous with it in a number of cases, such as pyroxenes and amphiboles; though it appears to be isomorphous with calcium in garnets. Magnesium and ferrous iron enter numerous mineral compounds isomorphously; and, in general, pyrogenetic minerals containing magnesium also contain ferrous iron in variable amounts. But there are iron-bearing compounds free from notable amounts of magnesium, some of which contain calcium.

$(Mg,Fe)SiO_3$. ORTHORHOMBIC PYROXENE. ENSTATITE and HYPERSTHENE. Metasilicate of magnesium with variable amounts of ferrous iron. The highest silicate of these elements in igneous rocks.

$$MgO \cdot SiO_2 = 60.0\ SiO_2,\ 40.0\ MgO = 100.$$
$$3\ MgO \cdot FeO \cdot 4\ SiO_2 = 55.5\ SiO_2,\ 27.7\ MgO,\ 16.8\ FeO = 100.$$
$$MgO \cdot FeO \cdot 2\ SiO_2 = 51.8\ SiO_2,\ 17.2\ MgO,\ 31.0\ FeO = 100.$$

Orthorhombic pyroxenes occur in rocks with considerable silicon and may be accompanied by quartz. But they do not appear to crystallize from magmas in which the silicon is not sufficient to make polysilicates with all the potassium and sodium present. They do not accompany leucite or nephelite. The corresponding orthorhombic amphiboles, *anthophillite, gedrite,* are not pyrogenetic minerals.

$Ca(Mg,Fe)(SiO_3)_2$, or $Ca(Mg,R)(SiO_3)_2$. DIOPSIDE-AUGITE. Metasilicates in which magnesium may be replaced by various elements and radicals, chiefly $\overset{II}{Fe}$, $\overset{III}{Fe}$, Al, Na; but in which calcium maintains an approximately fixed ratio to the other bases, 1 : 1. The maximum amount of MgO is about 17 per cent.

$Ca(Mg,R)_3(SiO_3)_4$. AMPHIBOLE. Metasilicate containing about the same amount of magnesium, but more of the other basic elements than in pyroxene, with the proportion of calcium approximately fixed, 1 : 3, as compared with the other elements and radicals. The maximum amount of MgO is about 19 per cent. Magnesium does not enter the zirconosilicates in notable amounts.

$(Mg,Fe)_2(SiO_4)$. OLIVINE. Orthosilicate of magnesium with variable amounts of ferrous iron, with from 52.0 to 32.0 MgO, and from 5.0 to 30.0 FeO. It commonly crystallizes from magmas low in silicon, but sometimes forms in magmas with sufficient silicon to form the metasilicates, enstatite, hypersthene, and consequently it may occur with pyrogenetic quartz.

$(Mg,Fe)_2(SiO_4)$ and $(K,H)_2(Al,Fe)_2(SiO_4)_2$. BIOTITE. An acid orthosilicate in which magnesium and iron enter in variable proportions, and as though an olivine molecule were combined with an iron-bearing muscovite molecule. MgO may vary from 29 to 1 per cent.

In the common pyrogenetic minerals, enstatite, hypersthene, olivine, and biotite, there is no calcium in combination with the magnesium.

$H_2(Mg,Fe)_4Al_8Si_{10}O_{37}$. CORDIERITE. $H_2O \cdot 4(Mg,Fe)O \cdot 4(Al_2O_3)$, 10 $SiO_2$. When Mg : Fe : : 7 : 2 the composition is 49.4 $SiO_2$, 33.6 $Al_2O_3$, 5.3 FeO, 10.2 MgO, 1.5 $H_2O$ = 100. Cordierite is a rare pyrogenetic mineral in some of the more siliceous rocks, especially granite.

$(\overset{I}{R}_6,\overset{II}{R}_3,\overset{III}{R}_2)SiO_5$. TOURMALINE. A complex silicate of aluminium and boron with magnesium, iron, or the alkalies, prominent. MgO may reach 14.5 per cent; little or no calcium.

$(Ca(Mg))_4Si_3O_{10}$ with $(Ca,Mg,Fe)_3((Al,Fe)O)_2SiO_4$. MELILITE. A silicate of calcium with small amounts of magnesium, iron, and aluminium. MgO from 6 to 8 per cent. Magnesium occurs in very small amounts in a number of other pyrogenetic silicates accompanying calcium or iron.

$(Fe,Mg,Ti)_2O_3$. PICROTITANITE. Magnesium-ilmenite, sometimes crystallizing in igneous rocks rich in magnesium and low in silicon.

$\overset{II}{R}\overset{III}{R}_2O_4$. SPINEL. $\overset{II}{R}$ = Mg,Fe(Mn) · $\overset{III}{R}$ = Al,Fe,Cr,(Mn). Aluminates, ferrates, and chromates of magnesium and iron for the most part. Those known to occur as pyrogenetic minerals containing notable amounts of magnesium are: ceylonite (pleonaste), $(Mg,Fe)Al_2O_4$; and picotite (Mg,Fe) $(Al,Fe,Cr)_2O_4$. In these the percentage of MgO varies from 10 to 20. Ceylonite occurs very sparingly in the more siliceous rocks, but picotite is common in those low in silicon, peridotites.

**Zn.** Zinc, though a bivalent element like calcium, is not closely similar to it in its chemical behavior, but is somewhat more like magnesium. It is of rare occurrence in igneous rocks and enters into the composition of very few pyrogenetic minerals. There is 18.15 ZnO in the glucinum silicate, danalite, which occurs in granite at Cape Ann, Mass., and elsewhere. Traces of zinc have been found in some olivine, and in fergusonite.

**Fe. Iron** differs from the other elements of Group II just noted, in that it may behave as a bivalent or trivalent element.

In some pyrogenetic compounds it enters only as a bivalent metal, in others it is only trivalent, but in many it is present in both forms. In its trivalent character it resembles aluminium somewhat, and may play the rôle of a base- or an acid-forming element. While mostly combined with silicon as a silicate it also occurs independently, crystallizing from igneous magmas as an oxide, $Fe_2O_3$, or more often as an iron ferrate, $\overset{II}{Fe}\overset{III}{Fe_2}O_4$, in the presence of quartz. Iron of both valencies will be included in the following discussion of its occurrences.

Fe. **Metallic Iron** is occasionally found in very small amounts in igneous rocks low in silica and rich in ferromagnesian minerals (basalts) at various localities. At Ovifak, Greenland, it occurs in this manner in masses of great size.

$Fe_2O_3$. Hematite is developed as a pyrogenetic mineral to some extent in rocks rich in silicon, or in alkalies and aluminium.

$(Fe,Ti)_2O_3$. Ilmenite. $FeO \cdot TiO_2$ or $(Fe,Ti)_2O_3$ with variable amounts of titanium, grading into magnetite, and sometimes containing magnesium, *picrotitanite,* or manganese. It crystallizes in igneous rocks of various kinds, from highly siliceous to those very low in silicon.

$\overset{II}{Fe}\overset{III}{Fe}O_4$. Magnetite. $FeO \cdot Fe_2O_3 = 31.0$ FeO, 69.0 $Fe_2O_3 = 100$. Iron ferrate, in which there may be magnesium, manganese, or titanium. It crystallizes from igneous magmas having a great variety of compositions from the most siliceous to the least so, consequently with or without quartz.

$\overset{II}{R}\overset{III}{R_2}O_4$. Spinel. $\overset{II}{R}$ = Mg,Fe(Mn), $\overset{III}{R}$ = Al,Fe,Cr,(Mn). Ferrates, aluminates, and chromates of magnesium and iron analogous to magnetite, but much less common as pyrogenetic minerals. Those in which iron is a notable component are: ceylonite (pleonaste), $(Mg,Fe)Al_2O_4$; picotite, $(Mg,Fe)(Al,Fe,Cr)_2O_4$; chromite, $FeCr_2O_4$. The first, pleonaste, sometimes occurs in the more siliceous rocks; picotite and chromite often occur in igneous rocks low in silicon and rich in magnesium and iron, peridotites.

$(Fe,Mg)_2(SiO_4)$ and $(K,H)_2(Al,Fe)_2(SiO_4)_2$. Biotite. An acid orthosilicate in which ferrous and ferric iron may be present in various proportions, being most abundant in *lepidomelane,* in which FeO may reach 30.0 per cent with 8.0 $Fe_2O_3$; or it may be 25.0 $Fe_2O_3$ with 7.0 FeO. Mica richest in iron often crystallizes from igneous magmas comparatively low in iron. It may form in rocks high in silicon or low in silicon.

$(Na\overset{III}{Fe})_2\overset{II}{Fe}(SiO_3)_5$. RIEBECKITE. $Na_2O \cdot FeO \cdot Fe_2O_3 \cdot 5\ SiO_2 = 50.5\ SiO_2,\ 26.9\ Fe_2O_3,\ 12.1\ FeO,\ 10.5\ Na_2O = 100$. A metasilicate in which iron appears both in the ferrous and ferric state. An amphibole crystallizing in alkalic magmas, especially in the more siliceous ones.

$Ca(Mg,R)_3(SiO_3)_4$. AMPHIBOLE. Metasilicates in which both ferrous and ferric iron may play a prominent rôle along with magnesium, calcium, aluminium, sodium, hydrogen, and fluorine. In *hornblende* there may be: 4.94 $Fe_2O_3$, 10.39 FeO (Butte granite); in *barkevikite*, 6.18 $Fe_2O_3$, 19.93 FeO (nephelite-syenite, Barkevik). There is a transition to riebeckite through the more sodic varieties. Amphiboles rich in iron and sodium occur in the highly sodic rocks, both high in silicon, and in those low in silicon. Amphiboles rich in iron with little or no sodium occur in the less siliceous rocks low in sodium.

$Na\overset{III}{Fe}(SiO_3)_2$. ACMITE. $Na_2O \cdot Fe_2O_3 \cdot 4\ SiO_2 = 52.0\ SiO_2,\ 34.6\ Fe_2O_3,\ 13.4\ Na_2O = 100$. A metasilicate in which iron is abundant in the ferric state only. A pyroxene crystallizing from igneous magmas rich in sodium with ferric iron, which may be highly siliceous, or low in silicon. It forms with other monoclinic pyroxenes an isomorphous compound, *ægirite-augite*.

$Ca(Mg,R)(SiO_3)_2$. DIOPSIDE-AUGITE. A metasilicate in which both ferrous and ferric iron occur in various proportions, but not so abundantly as in amphiboles crystallized from the same magma. FeO may be as high as 16 per cent in some cases, though commonly less than 7. $Fe_2O_3$ may reach 8 per cent, but it is oftener less than 5.

$(Mg,Fe)SiO_3$. ENSTATITE, HYPERSTHENE. Metasilicates of magnesium and ferrous iron, in which FeO may be as high as 28 per cent. They crystallize from the more siliceous rocks and from those with sufficient silicon to form metasilicates of the elements named.

$(Mg,Fe)_2SiO_4$. OLIVINE, FAYALITE. Orthosilicates of magnesium and ferrous iron. In common olivines the FeO may reach 12 per cent. In hyalosiderite it reaches 30 per cent. In fayalite, $Fe_2SiO_4$, there is 70.6 FeO. The most ferrous compound, fayalite, is rarely crystallized from igneous magmas in notable amounts, but may form in magmas low in magnesium, both

highly siliceous ones and those low in silica. It occurs with quartz in some cases, and with nephelite in others. Olivine is commonly formed in magmas low in silicon, but may crystallize in more siliceous ones together with quartz.

$(Ca,Mg,Fe)_3(Al,Fe)_2(SiO_4)_3$. GARNET. An orthosilicate in which ferrous and ferric iron may be present in various amounts. The more ferrous garnet, almandite, $Fe_3Al_2(SiO_4)_3$, with nearly 40 per cent of FeO, and some $Fe_2O_3$, occurs in the more siliceous igneous rocks, such as granites. The more ferric garnet, andradite (melanite), $Ca_3Fe_2(SiO_4)_3$, with a maximum of 31.5 per cent of $Fe_2O_3$, and variable amounts of FeO, crystallizes from the more alkalic igneous rocks.

$(\overset{I}{R}_6,\overset{II}{R}_3,\overset{III}{R}_2)SiO_5$. TOURMALINE. A complex silicate of aluminium and boron with magnesium, iron, or the alkalies prominent. FeO may reach 17 per cent. There is usually very little ferric iron present.

$(Ca(Mg))_4Si_3O_{10}$ with $(Ca,Mg,Fe)_3((Al,Fe)O)_2SiO_4$. MELILITE. A silicate of uncertain composition in which $Fe_2O_3$ may be 10.17 per cent, with little or no ferrous iron.

$H_2(Mg,Fe)_4Al_8Si_{10}O_{37}$. CORDIERITE. Rarely a pyrogenetic silicate which may contain 8.55 FeO.

$Na_{13}(Ca,Fe)_6Cl(Si, Zr)_{20}O_{52}$. EUDIALYTE (eucolite), a metasilicate in which there may be from 4 to 7 per cent of FeO, occurring in sodic magmas low in silicon.

$(Ca,Fe)_3(BO)_2(SiO_4)_2$. HOMILITE. A rare orthosilicate containing 19 per cent of FeO, occurring in nephelite-syenite pegmatite in Norway.

$Gl_2Fe(YO)_2(SiO_4)_2$. GADOLINITE. A basic orthosilicate with 14.3 FeO in the ideal compound. A rare mineral occurring in some granite pegmatites.

$Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$. EPIDOTE. A basic orthosilicate, containing ferric iron in varying amounts, up to 17 per cent and possibly more. Not commonly pyrogenetic.

$H\overset{II}{R}\overset{III}{R}_2Si_3O_{13}$. ALLANITE. $H_2O \cdot 4\,RO \cdot 3\,R_2O_3 \cdot 6\,SiO_2$, with $\overset{II}{R}$ = Ca, Fe, and $\overset{III}{R}$ = Al, Fe, Ce, Di, La, and smaller amounts of the yttrium group; $Fe_2O_3$ from 2 to 9 per cent; FeO from 1 to 13 per cent. A mineral widely distributed in very small amounts in the more alkalic rocks, chiefly in the more siliceous.

Iron enters into the composition of a number of rare titanates and silicotitanates, whose formulæ may be found under the heading of Titanium. They are: keilhauite, with about 6.0 $Fe_2O_3$; astrophyllite, with $Fe_2O_3$ from 2.53 to 8.51, FeO from 18.06 to 29.02; perovskite with sometimes 4.79 FeO.

Iron enters the rare columbates and tantalates found principally in granitic and syenitic pegmatites. The more ferriferous minerals of this kind are: columbite and tantalite with FeO from 1 to 17 per cent; tapiolite with 14.47 FeO; samarskite, with as much as 14.0 FeO in some varieties, and other minerals of this group with less.

$FeS_2$. PYRITE. Iron disulphide, 46.6 Fe, 53.4 S = 100. Of widespread occurrence in small amounts as a pyrogenetic mineral.

$FeCuS_2$. CHALCOPYRITE. 30.5 Fe, 34.5 Cu, 35.0 S = 100. A sulphide sometimes developed pyrogenetically.

$Fe_nS_{n+1}$. PYRRHOTITE. Composition somewhat variable, about 61.0 Fe, 39.0 S = 100. Accompanies pentlandite and chalcopyrite in gabbro in Norway and Canada.

(Fe,Ni)S. PENTLANDITE. 42.0 Fe, 22.0 Ni, 36.0 S = 100. Its occurrence in gabbro noted above.

**Ni,Co. Nickel and Cobalt** resemble iron closely, and accompany it in very small amounts. They do not characterize any pyrogenetic silicate minerals, but are found in traces in some pyrogenetic olivine in highly magnesian rocks, peridotites.

(Fe,Ni)S. PENTLANDITE. Sulphide of iron and nickel, with 22.0 Ni, sometimes occurring in considerable amounts with pyrrhotite and chalcopyrite in gabbro, at Sudbury, Ontario, and in Norway.

**Mn. Manganese** resembles iron to some extent in its chemical behavior, but has a wider range of valencies. However, in the pyrogenetic minerals it is generally considered to be bivalent or trivalent in different cases, and is isomorphous with bivalent or trivalent iron in the few compounds in which it is in notable amounts. It is one of the minor elementary constituents of igneous rocks. Traces of manganese occur in a number of pyrogenetic minerals containing iron, but it forms a notable component of only a few.

$Mn_3Al_2(SiO_4)_3$. SPESSARTITE. Manganese-aluminium garnet, $3\,MnO \cdot Al_2O_3 \cdot 3\,SiO_2$ = 36.4 $SiO_2$, 20.6 $Al_2O_3$, 43.0 MnO = 100. Ferrous iron replaces manganese to a greater or less extent, and ferric iron replaces aluminium. Spessartite occurs in some of the more siliceous igneous rocks.

$(Mn,Fe)_2(Mn_2S)Gl_3(SiO_4)_3$. HELVITE. If iron is absent the composition would be 32.5 $SiO_2$, 13.6 GlO, 51.0 MnO, 5.8 S = 102.9 less 2.9 O for S = 100. There may be as much as 15 per cent of FeO. Occurs in pegmatite veins of nephelite-syenite and of granite. A similar mineral, danalite, $(Fe,Zn,Mn)_2((Zn,Fe)_2S)Gl_3(SiO_4)_3$, with more iron, and zinc replacing manganese, occurs in granite associated with lithia-mica at Cape Ann, Mass., and near Gloucester, Mass.

Manganese occurs sparingly in the zirconosilicates; in låvenite, about 5.0 to 7.0 MnO; and less than 2.0 MnO in rosenbuschite and wöhlerite; in eudialyte (eucolite) about 3.0 MnO in some cases.

$\overset{I}{R}_4\overset{II}{R}_4Ti(SiO_4)_4$. ASTROPHYLLITE. Probably orthosilicate, with $\overset{I}{R}$ = H, Na, K, and $\overset{II}{R}$ = Fe, Mn, chiefly, including also $Fe_2O_3$. There may be 3.5 to 12.5 MnO. Occurs in nephelite-syenite pegmatite.

$(Fe,Mn)(Cb,Ta)_2O_6$. COLUMBITE, TANTALITE. Columbate and tantalate of iron and manganese, varying widely in composition. MnO may reach 16.25 per cent. Occur in granite pegmatites in numerous localities.

$Li(Fe,Mn)PO_4$. TRIPHYLITE. $Li(Mn,Fe)PO_4$. LITHIOPHILITE. Phosphates with variable amounts of iron and manganese. MnO ranging from 8.96 to 40.86 per cent. Occur in granite pegmatite with lithium silicates.

$(RF)RPO_4$. TRIPLITE. A phosphate of iron and manganese, and less calcium and magnesium, in variable proportions. MnO from 23.25 to 54.14 per cent. Occurs in granite pegmatite.

$(Mn,Fe)P_2O_8 \cdot (Mn,Fe)OH_2$. TRIPLOIDITE. A phosphate similar to triplite with (OH) replacing F. There is about 43 to 48 per cent MnO. Occurs in granite pegmatite at Branchville, Conn.

**Gl. Glucinum** (beryllium) is the weakest basic element of Group II. Its oxides and hydroxides are basic, but are also feebly acid toward active bases. It occurs in small amounts in igneous rocks in the more alkalic, and usually in the most siliceous. It does not enter compounds isomorphously to any considerable extent. Its compounds are rather definite and distinct.

$GlAl_2O_4$. CRYSOBERYL. $GlO \cdot Al_2O_3$ = 80.2 $Al_2O_3$, 19.8 GlO = 100. Glucinum aluminate, not isomorphous with magnesium aluminate, spinels. Occurs in granite pegmatites.

$Gl_3Al_2(SiO_3)_6$. BERYL. 3 $GlO \cdot Al_2O_3 \cdot 6\ SiO_3$ = 67.0 $SiO_2$, 19.0 $Al_2O_3$, 14.0 GlO = 100. A metasilicate in which $Na_2,Li_2,Cs_2,H_2$ are sometimes present replacing Gl. Beryl at Hebron, Me., contains 3.6 $Cs_2O$. The mineral is common in granite pegmatites, and is sometimes of great size, in one case weighing nearly two and one-half tons, Grafton, Mass.

$Gl_2SiO_4$. PHENACITE. 2 $GlO \cdot SiO_2$ = 54.45 $SiO_2$, 45.55 GlO = 100. Glucinum orthosilicate, occurring sparingly in granite pegmatite.

$H_2Gl_4Si_2O_9$. BERTRANDITE. $H_2O \cdot 4\ GlO \cdot 2\ SiO_2$ = 50.3 $SiO_2$, 42.1 GlO. 7.6 $H_2O$ = 100. Probably a basic orthosilicate; a rare mineral occurring in granite pegmatite.

$NaCa(GlF)(SiO_3)_2$. LEUCOPHANITE. 49.4 $SiO_2$, 10.3 GlO, 23.0 CaO, 12.8 $Na_2O$, 7.9 F = 103.4 less 3.4 O for F = 100.

$NaCa_2Gl_3FSi_3O_{10}$. MELIPHANITE. 46.9 $SiO_2$, 13.1 GlO, 29.1 CaO, 8.1 $Na_2O$, 5.0 F = 102.2 less 2.2 O for F = 100. Fluosilicates occurring in nephelite-syenite pegmatites in Norway.

$(Mn,Fe)_2(Mn_2S)Gl_3(SiO_4)_3$. HELVITE. $(Fe,Zn,Mn)_2((Zn,Fe)_2S)\ Gl_3(SiO_4)_3$. DANALITE. Orthosilicates containing from 10 to 14 per cent of GlO. Occurring in a few localities in granite pegmatite.

$Gl_2Fe(YO)_2(SiO_4)_2$. GADOLINITE. 2 $GlO \cdot FeO \cdot 2\ Y_2O_3 \cdot 2\ SiO_2$=23.9 $SiO_2$, 51.8 yttrium oxides ($Y_2O_3$, $Ca_2O_3$, $(Di,La)_2O_3$), 14.3 FeO, 10.0 GlO = 100. A basic orthosilicate occurring in granite pegmatites.

$NaGlPO_4$. BERYLLONITE. 55.9 $P_2O_5$, 19.7 GlO, 24.4 $Na_2O$ = 100. A rare phosphate occurring in granite pegmatite at Stoneham, Me., with herderite and phenacite.

$(CaF)GlPO_4$. HERDERITE. 44.31 $P_2O_5$, 15.76 GlO, 33.21 CaO, 11.32 F = 104.60 less 4.6 O for F = 100. Hydroxyl may partly replace fluorine. Occurs in granite pegmatite in several localities.

## SUMMARY FOR GROUP II

Barium and strontium occur only in traces in pyrogenetic minerals, chiefly in feldspars. Barium in notable amount is a constituent of cappelenite, a rare mineral in nepheline-syenite in one locality in Norway.

Calcium is a common element in considerable amounts in many silicates, chiefly feldspars, monoclinic pyroxenes and amphiboles, and in numerous rare minerals. It also occurs in titanates, niobates, and phosphates. It is a more active base-forming element than magnesium and iron, and is never found uncombined with an acid radical. It enters metasilicates and orthosilicates, but is not found as a polysilicate. It is less constantly associated with aluminium than are the elements of Group I, and occurs in numerous compounds without aluminium.

Magnesium, a less active element than calcium, is commonly present in igneous rocks, and often abundant. It is chiefly in silicate compounds, and rarely occurs as a constituent of aluminates, ferrates, or chromates, in which cases the magmas were generally low in silicic acid. It is less frequently met with in the rarer minerals than is calcium. It is a more active base-forming element than iron, and is never found uncombined with an acid radical. It forms chiefly metasilicates and orthosilicates, frequently without aluminium; the most aluminous pyrogenetic magnesian mineral is biotite or phlogopite.

Iron is usually present in igneous rocks, but in very variable amounts. As a less active element than magnesium and calcium, and one having several valencies, it is not so universally combined with silicic or other acids as these elements are in igneous rocks, but occurs commonly as oxide, in the ferric state, $Fe_2O_3$, and as iron ferrate. It is even present in the metallic state in some instances. It occurs in a great variety of compounds, oftenest associated with magnesium. It enters chiefly silicates, but also titanates, tantalates, columbates, and phosphates; and besides occurring as oxides, combines with sulphur to form several compounds.

Manganese, much like iron chemically, is never present in considerable amounts in igneous rocks. It enters compounds with iron, usually in very small amounts. But in some of the rare

pyrogenetic minerals, silicates, tantalates, columbates, and phosphates, it is a notable component.

Glucinum (beryllium), the least active element of this group, is a rare constituent of igneous rocks, and occurs chiefly in certain silicate and phosphate minerals in pegmatites of granite and syenite.

Zinc has only been found in traces in a few igneous rocks, and cadmium and mercury are not known to occur pyrogenetically.

### GROUP III

Cerium, Lanthanum, Didymium (neodymium, praseodymium), Ytterbium, Yttrium, and Erbium are rare elements of somewhat uncertain properties, owing to their close resemblance to one another. They are trivalent and usually occur together in compounds in varying proportions. Thallium, Indium, and Gallium have not been noted in pyrogenetic compounds.

Aluminium, the common element in the group, is trivalent in all its compounds, and, like trivalent iron, with which it is often associated, it is weakly basic in some compounds with strong acids, and acidic in others with strong bases. Both sets of compounds may be hydrolyzed by water, the second kind more readily than the first. The same is true of similar compounds with trivalent iron, chromium, etc.

Boron, though trivalent like aluminium, almost always enters the acid radical in its compounds. In its chemical behavior it is more like silicon and carbon.

**Ce, La, Di, Y, Er. Cerium, Lanthanum, Didymium** (neodymium, praseodymium), **Ytterbium, Yttrium,** and **Erbium** enter a number of silicate compounds, and a greater number of columbates and tantalates, besides others. Owing to the great similarity of these elements with one another their compounds will be described together. They occur mostly in pegmatites of granite and syenite, but are also disseminated somewhat widely in small amounts in various kinds of igneous rocks. It is to be noted that these elements, though trivalent like aluminium, are not isomorphous with it, and in most instances enter compounds free from aluminium.

$H\overset{II}{R}\overset{III}{R}_3Si_3O_{13}$. Allanite. $H_2O \cdot 4\,RO \cdot 3\,R_2O_3 \cdot 6\,SiO_2$, with $\overset{II}{R}$ = Ca, Fe, and $\overset{III}{R}$ = Al, Fe, Ce, Di, La, and in smaller amounts Y, Er; proportions variable. The following are the largest percentages of the rare oxides found in different analyses: 33.76 $Ce_2O_3$, 16.34 $Di_2O_3$, 8.10 $La_2O_3$, 4.20 $Y_2O_3$, 2.00 $Er_2O_3$. Allanite is a cerium-epidote occurring in small amounts in a great variety of igneous rocks, chiefly the more siliceous kinds.

$Gl_2FeY_2Si_2O_{10}$. GADOLINITE. $2\,GlO \cdot FeO \cdot 2\,Y_2O_3 \cdot 2\,SiO_2$, a basic orthosilicate with 51.8 yttrium oxides, which are partly replaced by oxides of cerium, lanthanum, and didymium. The highest percentages noted in the analyses are: 47.06 $Y_2O_3$ (yttrium earths), 11.10 $Ce_2O_3$, 21.23 $(Di,La)_2O_3$. Gadolinite occurs in granite pegmatites associated with allanite.

$Y_2O_3,ThO_2$, etc., $SiO_2$. YTTRIALITE. A silicate of thorium and the yttrium metals chiefly of indefinite composition, containing 46.50 $Y_2O_3$ (yttrium earths), 1.86 $Ce_2O_3$, 2.94 $(LaDi)_2O_3$. A rare mineral associated with gadolinite in granite pegmatite in Llano Co., Texas.

$3\,BaSiO_3 \cdot 2\,Y_2(SiO_3)_3 \cdot 5\,YBO_3$. CAPPELENITE.

$12\,(H_2,Ca)SiO_3 \cdot 3\,(Y,Ce)BO_3 \cdot 2\,H_2(Th,Ce)O_2F_2 \cdot 8\,(Ce,La,Di)OF$. MELANOCERITE.

$6\,(H_2,Ca)SiO_3 \cdot 2\,(Ce,Di,Y)BO_3 \cdot 3\,H_2(Ce,Th)O_2F_2 \cdot 2\,LaOF$. CARYOCERITE.

$2\,(H_2,Ca_2,Ca)SiO_3 \cdot (Ce,La,Di,Y)BO_3 \cdot H_2(Ce,Th)O_2F_2$. TRITOMITE.

Complex silicates of the rare elements with boron and fluorine. In cappelenite 52.62 $Y_2O_3$, 2.97 $La_2O_3$, 1.29 $Ce_2O_3$, 0.80 $ThO_2$ = 57.68. In melanocerite 9.17 $Y_2O_3$, 20.76 $Ce_2O_3$, 7.67 $Di_2O_3$, 12.94 $La_2O_3$, 3.68 $CeO_2$, 1.66 $ThO_2$. In caryocerite 2.21 $Y_2O_3$, 14.83 $Ce_2O_3$, 14.34 $La_2O_3$, 6.75 $Di_2O_3$, 5.89 $CeO_2$, 13.64 $ThO_2$. In tritomite 10.65 $Ce_2O_3$, 16.31 $La_2O_3$, 5.57 $Di_2O_3$, 2.97 $Y_2O_3$, 11.69 $CeO_2$, 9.51 $ThO_2$. These minerals occur sparingly in the nephelite-syenite pegmatites in Norway.

$\left[\begin{matrix} F_6\overset{IV}{R}_3 \\ F\overset{III}{R} \end{matrix}\right](\overset{I}{R}_2)_4\overset{II}{R}_{13}\overset{III}{R}_2(SiO_4)_{12}$. JOHNSTRUPITE. $\overset{I}{R}$ = Na, H; $\overset{II}{R}$ = Ca, Mg; $\overset{III}{R}$ = Ce, Y, Al, Fe; $\overset{IV}{R}$ = Ti, Zr. The group in the brackets is regarded as corresponding to the bivalent group $(\overset{III}{R}OH)$ in epidote. Similar formulas have been suggested for *mosandrite* and *rinkite*. Complex silicates of the cerium elements and others, occurring in nephelite-syenite pegmatites.

| | $SiO_2$ | $TiO_2$ | $ZrO_2$ | $ThO_2$ | $CeO_2$ | $Ce_2O_3$ | $Y_2O_3$ | $Al_2O_3$ | $Fe_2O_3$ | CaO |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Johnstrupite | 30.50 | 7.57 | 2.84 | 0.79 | 0.80 | 12.71[a] | 1.11 | 1.52 | 0.50 | 27.76 |
| 2. Mosandrite | 30.71 | 5.33 | 7.43 | 0.34 | 6.34 | 10.45[a] | 3.52 | —— | 0.56 | 22.53 |
| 3. Rinkite | 29.08 | 13.36 | —— | —— | —— | 21.25[a] | 0.92 | —— | 0.44[b] | 23.26 |

| | MgO | MnO | $Na_2O$ | $K_2O$ | $H_2O$ | F | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 1.63 | tr. | 6.67 | 0.12 | 1.41 | 5.98 | = 101.91 | less O for F | 2.50 | = 99.41 |
| 2. | 0.63 | 0.45 | 2.44 | 0.38 | 7.70 | 2.06 | = 100.87 | " | 0.86 | = 100.01 |
| 3. | —— | —— | 8.98 | —— | —— | 5.82 | = 103.11 | " | 2.45 | = 100.66 |

[a] Incl. $La_2O_3$, $Di_2O_3$. [b] FeO.

$Ca_3(Ce,La,Di)_4Si_3O_{15}$. BECKELITE, with very small amounts of zirconium, yttrium metals and the alkalies. Occurs in nephelite-syenite (mariupolite) in Russia.

The cerium elements occur in small amounts in the zirconosilicates, *eudialyte* (eucolite), 2.5 to 5.2 $Ce(La,Di)_2O_3$, and also in rosenbuschite, 2.38 $La_2O_3$ with a little Ce, and a trace of Di. Yttrium is present to a slight extent in titanite from Plauen Grund near Dresden, and in that in a granite pegmatite at Slättkåra, Sweden, and in eucolite-titanite in nephelite-syenite in Norway.

The cerium and yttrium metals enter the titanosilicate compound, keilhauite, with from 8.16 to 12.08 $Ce_2O_3,Y_2O_3$; and to a slight extent in a

variety of titanite in Norway. They are present in small amounts in the columbates and tantalates: pyrochlore, hachettolite, microlite. In annerödite there is about 10.0 ($Ce_2O_3,Y_2O_3$); in hielmite as much as 6.0 of both in some cases; in polymignite about 13 per cent. These minerals occur in pegmatite veins, in some cases of granite, in others of nephelite-syenite. Cerium and yttrium are more abundant in the following compounds:

$\overset{III}{R}(Cb,Ta)O_4$. FERGUSONITE with $\overset{III}{R}$ = Y, Er, Ce. Metacolumbate (and tantalate) of yttrium with erbium, cerium, uranium, etc., in varying amounts; also iron, calcium, etc. The highest percentages of the rare oxides found in the analyses are: 28.81 $Y_2O_3$, 13.95 $Er_2O_3$, 9.26 $Ce_2O_3$. Occurs in granite pegmatites.

$\overset{II}{R}_3\overset{III}{R}_2(Cb,Ta)_6O_{21}$. SAMARSKITE. $\overset{II}{R}$ = Fe, Ca, $UO_2$, etc.; $\overset{III}{R}$ = Y, Er, Ce, etc. In the analyses are found 4.78 $Ce_2O_3(Di,La)_2O_3$, 14.49 $Y_2O_3$, 10.80 $Er_2O_3$. Occurs in granite pegmatites.

$\overset{II}{R}\overset{III}{R}_2(Ta,Cb)_4O_{15} + 4\,H_2O$. YTTROTANTALITE. $\overset{II}{R}$ = Fe, Ca; $\overset{III}{R}$ = Y, Er, Ce, etc.; contains 10.52 $Y_2O_3$, 6.71 $Er_2O_3$, 2.22 $Ce_2O_3$. It occurs in granite pegmatite at Ytterby, Sweden.

$\overset{III}{R}_2Cb_4O_{13} \cdot \overset{III}{R}_2(Ti,Th)_5O_{13}$. ÆSCHYNITE. A columbate and titanate (thorate) of the cerium metals with a little iron and calcium; 18.49 $Ce_2O_3$, 5.60 $La_2(Di_2)O_3$, 1.12 $Y_2O_3$. Occurs in granite pegmatite.

$\overset{III}{R}(CbO_3)_3 \cdot \overset{III}{R}_2(TiO_3)_3 \cdot 3/2\,H_2O$. EUXENITE. A columbate and titanate of yttrium, erbium, cerium, and uranium. In different analyses, 27.48 $Y_2O_3$, 9.03 $Er_2O_3$, 3.50 $Ce_2O_3$. Occurs in granite pegmatite in Norway.

$\overset{III}{R}(CbO_3)_3 \cdot 2\,\overset{III}{R}(TiO_3)_3 \cdot 3\,H_2O$. POLYCRASE. Similar to euxenite, with 23.62 $Y_2O_3$, 8.84 $Er_2O_3$, 2.94 $Ce_2O_3$. Occurs in granite pegmatites.

$(Y,Ce,Er)PO_4$. XENOTIME. $(Ce,La,Di)PO_4$. MONAZITE. Phosphates of the yttrium and cerium metals in different proportions. In xenotime from Georgia, 54.13 $Y_2O_3$, 11.03 $Ce_2O_3(La_2,Di_2)O_3$; in one from Narestö, 30.23 $Y_2O_3$, 24.34 $Er_2O_3$, 0.96 $Ce_2O_3$. In monazite from Narestö, 30.58 $Ce_2O_3$, 29.21 $La_2O_3$, 0.78 $Y_2O_3$. Both minerals occur in granite pegmatites.

These elements also enter into uraninite in variable amounts up to 10 per cent, the mineral being found in granite pegmatites.

**Al. Aluminium** is one of the common elements in igneous rocks, and enters a number of compounds, the most abundant and common being silicates. It also occurs independently of silicic acid. Its most frequent compounds contain the alkalic elements, K, Na, Li. Its intermediate position in the Mendeléef series corresponds to its weakly basic or acid behavior toward other elements. It acts as a base toward a strong acid, and as an acid toward a strong base. Consequently the fixed relation between it and the alkalic elements in most of the aluminous silicates may be the result of their being aluminosilicates. While

in the non-alkalic or slightly alkalic compounds, such as some pyroxenes and amphiboles, the highly variable relation between aluminium and the basic elements indicates that in these compounds it plays the rôle of a basic element, replacing the others isomorphously.

$Al_2O_3$. CORUNDUM. Aluminium oxide, crystallizing independently in igneous magmas, rich in aluminium, especially in some granites, syenites, and nephelite-syenites.

$GlAl_2O_4$. CHRYSOBERYL. $GlO \cdot Al_2O_3 = 80.2\ Al_2O_3$, $19.8\ GlO = 100$. A rare aluminate formed in some granite pegmatite.

$\overset{II}{R}Al_2O_4$. SPINELS. Aluminates with some ferric iron and chromium, in which R = Mg, Fe (Mn); occurring rarely or in very small amounts. Ceylonite (pleonaste), $(Mg,Fe)Al_2O_4$, with 59.0 to 60.0 $Al_2O_3$, is a rare mineral in some granites, nephelite-syenites, and other rocks. Picotite, $(Mg,Fe)(Al,Fe,Cr)_2O_4$, with 56.0 $Al_2O_3$, is more common in some rocks low in silica, peridotites.

$(AlO)_{16}Al_4(SiO_4)_7$. DUMORTIERITE. 10 $Al_2O_3$, 7 $SiO_2$, yielding 70.8 $Al_2O_3$, 29.2 $SiO_2$ = 100. Boron may be present in small amounts. A rare mineral in some granite pegmatites.

$Al_2SiO_4(O,F_2)$. TOPAZ. A silicate of aluminium with fluorine and some hydroxyl. When the ratio of $O : F_2 = 5 : 1$, then 33.3 $SiO_2$, 56.5 $Al_2O_3$, 17.6 F = 107.4 less 7.4 O for F = 100. Occurs chiefly in granite pegmatites.

$\overset{I}{R}_6SiO_5$. TOURMALINE. A complex silicate of aluminium and boron, with magnesium, iron, and the alkalies present in subordinate amounts. $Al_2O_3$ mostly from 30 to 44 per cent. Frequently developed in granite pegmatites.

$2\overset{I}{R}O \cdot 7\overset{II}{R}O \cdot 11\overset{III}{R}_2O_3 \cdot 7SiO_2$ (?). GRANDIDIERITE. Silicate of aluminium, 52.8 $Al_2O_3$, with iron, magnesium, calcium, and the alkalies; occurring in granite pegmatite in Madagascar.

$CaAl_2(SiO_4)_2$. ANORTHITE. An orthosilicate with 36.7 $Al_2O_3$, isomorphous with albite, and forming with it lime-soda-feldspars, occurring in many kinds of rocks.

$(H,K)Al(SiO_4)$. MUSCOVITE, in part, also more siliceous, with 38.5 $Al_2O_3$ and less. Sometimes containing iron and magnesium. Occurs in granite, syenite, nephelite-syenite and their pegmatites.

$HKLiAl_3(SiO_4)_3$ and $K_3Li_3(AlF_2)_3Al(Si_3O_8)_3$. LEPIDOLITE, with 27.3 $Al_2O_3$ and less; grading through varieties with iron to zinnwaldite. These micas occur in granites and granite pegmatites.

$K_2Na_6Al_8Si_9O_{34}$. NEPHELITE. An orthosilicate with 33 $Al_2O_3$, occurring chiefly in highly alkalic rocks low in silicon.

$H_6Na_6Ca(NaCO_3)_2Al_6(SiO_4)_9$. CANCRINITE, an orthosilicate, somewhat like nephelite, with 29.0 $Al_2O_3$. Associated with nephelite in some rocks.

$Na_4(AlCl)Al_2(SiO_4)_3$. SODALITE, with 31.6 $Al_2O_3$.

$(Na_2,Ca)_2(NaSO_4 \cdot Al)Al_2(SiO_4)_3$. HAÜYNITE. $Na_4(NaSO_4 \cdot Al)Al_2(SiO_4)_3$. NOSELITE. With 27.0 $Al_2O_3$. Orthosilicates crystallizing from alkalic magmas generally rich in aluminium and low in silicon. Nephelite-syenites and equivalent lavas.

$LiAl(SiO_3)_2$. SPODUMENE. A metasilicate with 27.4 $Al_2O_3$, occurring in granite pegmatites.

$NaAl(SiO_3)_2$. JADEITE. A metasilicate, with 25.2 $Al_2O_3$, of doubtful pyrogenetic occurrence.

$NaAl(SiO_3)_2 + H_2O$. ANALCITE. Hydrous metasilicate with 23.2 $Al_2O_3$ occasionally pyrogenetic in alkalic rocks low in silicon.

$KAl(SiO_3)_2$. LEUCITE. A metasilicate with 23.5 $Al_2O_3$, crystallized in potassic rocks low in silicon.

$H_2Cs_4Al_4(SiO_3)_9$. POLLUCITE. A very rare metasilicate, with 16.0 $Al_2O_3$ occurring in granite.

$Gl_3Al_2(SiO_3)_6$. BERYL. A metasilicate with 19.0 $Al_2O_3$ developed in granite pegmatite.

$NaAl(Si_3O_8)$. ALBITE. A polysilicate with 19.5 $Al_2O_3$; isomorphous with anorthite, $CaAl_2(SiO_4)_2$, and forming mixed compounds in all proportions, so that the alumina in the lime-soda-feldspars ranges from 19.5 to 36.7 per cent.

$KAl(Si_3O_8)$. ORTHOCLASE (microcline). A polysilicate with 18.4 $Al_2O_3$. Occurs widely in igneous rocks, especially in the more potassic and more siliceous.

$LiAl(Si_2O_5)_2$. PETALITE. A disilicate with 16.7 $Al_2O_3$. Of rare occurrence in granite pegmatites.

$(H,K)_2(Al,Fe)_2(SiO_4)_2$ and $(Mg,Fe)_2(SiO_4)$. BIOTITE. An orthosilicate with variable amounts of aluminium, owing to its replacement by iron. 12.0 to 20.0 $Al_2O_3$.

$H_2(Mg,Fe)_4Al_8Si_{10}O_{37}$. CORDIERITE, with 33.6 $Al_2O_3$, rarely occurs as a pyrogenetic mineral in granite.

$Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$. EPIDOTE, with from 20.0 to 33.0 $Al_2O_3$, is seldom a primary mineral in granite.

$(Ca,Fe)_2(AlOH)(Al,Ce,Fe)_2(SiO_4)_3$. ALLANITE, with from 6.0 to 23.0 $Al_2O_3$, is a common pyrogenetic mineral in very small amounts.

$(Ca,Mg,Fe)_3(Al,Fe)_2(SiO_4)_3$. GARNET. An orthosilicate with variable amounts of $Al_2O_3$, from 15 to 22 per cent. Of widespread occurrence in small amounts.

$Ca(\overset{II}{R},(AlOH))_3(SiO_3)_4$. AMPHIBOLE. Metasilicates in which aluminium is present in variable amounts, probably in a basic radical. The percentage of $Al_2O_3$ in pyrogenetic hornblendes varies from 12.0 to 18.0. In the more alkalic varieties it is less.

$Ca(\overset{II}{R},(AlOH))(SiO_3)_2$. PYROXENE. Metasilicates with variable amounts of aluminium, as in amphibole, but generally in smaller amounts. In many augites less than 10.0 $Al_2O_3$.

$(Ca,Mg,Fe)_3((Al,Fe)O)_2(SiO_4)_2$ with $(Ca,Mg)_4Si_3O_{10}$ (?). MELILITE. A silicate of uncertain composition which contains from 3.4 to 10.17 $Al_2O_3$; occurring in rocks very low in silicon.

Aluminium occurs in very small amounts in the analysis of other pyrogenetic silicates. It enters into the composition of two rare titanosilicates: keilhauite with about 6.0 $Al_2O_3$ and astrophyllite, with as much as 4.0 $Al_2O_3$ in some varieties. It is a prominent component of one pyrogenetic phosphate where it accompanies the alkali metals.

$Li(AlF)PO_4$. AMBLYGONITE, with 34.4 $Al_2O_3$, occurs in granite pegmatite.

The general absence of the trivalent yttrium and cerium elements from the common aluminium compounds shows their lack of close isomorphous relations. The presence of trivalent iron in isomorphous mixture with aluminium in some mineral compounds and its complete absence from others indicates that their chemical similarity is only partial. The occurrence of trivalent iron in pyrogenetic compounds is discussed in connection with the occurrence of bivalent iron.

**Cr. Chromium**, a hexavalent element in some compounds, also possesses other valencies, and is commonly reckoned as trivalent in the few pyrogenetic minerals into which it enters. In these it is isomorphous with trivalent iron and aluminium.

$FeCr_2O_4$. CHROMITE. 68.0 $Cr_2O_3$, 32.0 FeO = 100. It may grade by accession of magnesium and ferric iron and aluminium into the following mineral:

$(Mg,Fe)(Al,Fe,Cr)_2O_4$. PICOTITE, a chromium spinel. Both of these minerals occur in igneous rocks rich in magnesium and iron, and poor in silicon, the peridotites.

$3\,CaO \cdot Cr_2O_3 \cdot 3\,SiO_2$. UVAROVITE. 35.9 $SiO_2$, 30.6 $Cr_2O_3$, 33.5 CaO = 100. Aluminium may be present replacing the chromium. The mineral is associated with chromite in altered peridotite. There may be a question as to its pyrogenetic origin.

**B. Boron**, though a trivalent element and a member of Group III, is so much of a non-metal that it acts as an acidic element forming acids and not

bases. Its behavior is more like that of silicon than that of aluminium. It is a rare element in igneous rocks, entering into the composition of only one pyrogenetic mineral of any general occurrence, tourmaline.

$4\ H_2O \cdot 2\ Na_2O \cdot 8\ Al_2O_3 \cdot 3\ B_2O_3 \cdot 12\ SiO_2$, or $3\ H_2O \cdot 12\ MgO \cdot 5\ Al_2O_3 \cdot 3\ B_2O_3 \cdot 12\ SiO_2$. TOURMALINE. A complex silicate of aluminium and boron and a small amount of other elements, with about 10.0 $B_2O_3$; occurring chiefly in granite pegmatites.

$(Ca,Fe)_2(BO)_2(SiO_4)_2$. HOMILITE. 32.1 $SiO_2$, 18.7 $B_2O_3$, 19.3 FeO, 29.9 CaO = 100. A rare mineral in nephelite-syenite pegmatite in Norway.

$3\ BaSiO_3 \cdot 2\ Y(SiO_3)_3 \cdot 5\ YBO_3$. CAPPELENITE. A borosilicate of yttrium and barium with about 17 $B_2O_3$. In the closely related mineral, melanocerite, there is about 3.2 $B_2O_3$; in caryocerite about 4.7 $B_2O_3$; in tritomite about 8.0 $B_2O_3$.

Other boron minerals appear to be of secondary origin.

## SUMMARY FOR GROUP III

The cerium and yttrium metals form rare compounds, mostly columbates and tantalates, less often silicates and phosphates, that occur chiefly in granitic and syenitic pegmatites. The cerium metals in the silicate allanite are of widespread occurrence in very small amounts.

Aluminium, one of the most abundant components of igneous rock, enters chiefly the alkali silicates, feldspars, nephelite, leucite, and the sodalites. It is present in numerous ferromagnesian silicates in smaller amounts, and also occurs in numerous less common silicates. It sometimes appears as an oxide, uncombined with silicic acid, and occasionally forms aluminates. It is a prominent constituent in one rare phosphate. Aluminium is most abundant in magmas rich in alkalies with moderate or high silicon.

Trivalent iron was described with bivalent iron in Group II. It accompanies aluminium in numerous ferromagnesian silicates, but is absent from the feldspars and feldspathic minerals. It is commonly present in small amounts as oxides, or ferrates, and in certain localities is a chief component of the rocks which are very low in silicon.

Chromium, which is much like iron, is rarely present in notable amounts, but is found in traces in rocks rich in iron and magnesium.

Boron enters few silicate compounds, chiefly tourmaline, and occurs in granitic and syenitic pegmatites.

## GROUP IV

THORIUM, CERIUM, ZIRCONIUM, and TITANIUM are tetravalent elements with lower valencies in some cases. Cerium has been mentioned with the trivalent elements. Thorium is a rare element always entering the basic radical of a compound. Zirconium is common in small amounts, and titanium is still commoner. They are feebly base-forming as well as feebly acid-forming. They often enter acid radicals with silicon, which they resemble somewhat chemically, but may also act as bases in silicates.

LEAD, TIN, and GERMANIUM are extremely rare elements in igneous rocks. They are both tetravalent and bivalent. In this respect they resemble carbon more closely than silicon. The oxides and hydroxides of these three elements are basic, the most basic first in the order named. The three hydroxides are also acidic, the most acidic last in the order named.

SILICON and CARBON are tetravalent elements, but carbon is also bivalent. They both enter the acidic radical of compounds exclusively, and while very similar in some of their chemical characters, they do not replace one another isomorphously in pyrogenetic compounds. In fact, carbon is extremely scarce in such minerals. Acids formed from these elements, though more active than those sometimes formed by certain trivalent elements, are rather weak when compared with acids formed by elements in the succeeding groups.

**Th. Thorium** is a quadrivalent element always forming bases. It is closely related, chemically, to cerium, which, however, is also trivalent, and is found associated with the cerium metals in a number of rare pyrogenetic compounds. Thorium is also similar in some respects to base-forming zirconium, and enters compounds isomorphously with it to a slight extent.

$ThSiO_4$. THORITE. $ThO_2 \cdot SiO_2 = 18.5\ SiO_2, 81.5\ ThO_2$. Uranium may be present, sometimes as much as 9.78 $U_2O_3$. Occurs in syenite in several localities in Norway.

$6\ (H_2,Ca)SiO_3 \cdot 2(Ce,Di,Y)BO_3 \cdot 3\ H_2(Ce,Th)O_2F_2 \cdot 2\ LaOF$. CARYOCERITE. A complex silicate containing 13.64 $ThO_2$, occurring in nephelite-syenite in Norway. There is 9.51 $ThO_2$ in the similar mineral tritomite, and 1.66 $ThO_2$ in melanocerite, which occur in a similar manner in the same region.

$R_2O_3 \cdot 2\ SiO_2$. YTTRIALITE. A silicate of thorium and the yttrium metals chiefly, with 12.0 $ThO_2$, occurring with gadolinite in a granite pegmatite in Llano Co., Texas. There is a small amount of thorium in some crystals of allanite, and traces of it in other silicates of the cerium metals.

$RCb_2O_6 \cdot R(Ti,Th)O_3$. PYROCHLORE. A columbate with 5.0 to 7.56 $ThO_2$, occurring in nephelite-syenite in Norway.

$\overset{III}{R}_2Cb_4O_{12} \cdot \overset{III}{R}_2(Ti,Th)_5O_{13}$. ÆSCHYNITE. A columbate, titanate, and thorate (?), with 15.75 $ThO_2$, occurring in granite.

$(Ce,La,Di)PO_4$. MONAZITE. Thorium is generally present in varying proportions, usually accompanied by silicon in the proper amount to make thorium silicate, thorite. It is not known whether this is present as a mechanical mixture or not. $ThO_2$ from 9 to 12 per cent in some cases.

$UO_3,UO_2 \cdot ThO_2$, etc. URANINITE. A complex uranium compound with variable amounts of $Th_2O_3$, up to 9.79 per cent, occurring in granite pegmatite.

**Zr. Zirconium** is a quadrivalent element having the property of sometimes forming weak bases, sometimes weak acids. It is similar in this to titanium, which is near it in the same group, the two being associated with silicon, and entering compounds isomorphously with it. In the silicates zirconium in some cases plays the rôle of base, in others of acid, replacing silicon in part. It is of common occurrence in small amounts in nearly all igneous rocks, being most abundant in the highly alkalic rocks with a moderate amount of silicon.

$ZrO_2$. BADDELEYITE, with a little iron. A very rare mineral, occurring locally in nephelite-syenite at Alnö, Sweden.

$ZrSiO_4$. ZIRCON. Zirconium orthosilicate, 32.8 $SiO_2$, 67.2 $ZrO_2$. A common mineral in small amounts in the more siliceous rocks, more abundant in the more alkalic.

$H_2(Na_2,Ca)(Zr(OH)_2)(SiO_3)_3$. CATAPLEIITE. When Ca = 0, 46.1 $SiO_2$, 28.8 $ZrO_2$, 15.9 $Na_2O$, 9.2 $H_2O$ = 100. The analyses show from 29.0 to 40.0 $ZrO_2$. Occurs in nephelite-syenite in Norway.

$\overset{I}{R}_4\overset{II}{R}_3Zr(SiO_3)_7$. EUDIALYTE (eucolite). $\overset{I}{R}$=Na chiefly, also K, H; $\overset{II}{R}$=Ca chiefly, also Fe, Mn, and Ce(OH); $ZrOCl_2$ in part replacing $SiO_2$; Cb(Ta) may be present in small amount. In eucolite at Barkevik, 45.15 $SiO_2$, 3.52 $Ta_2O_5$, 12.51 $ZrO_2$, 4.80 $Ce_2O_3$, 0.32 $Y_2O_3$, 3.90 FeO, 3.60 MnO, 12.11 CaO, 11.17 $Na_2O$, 0.11 $K_2O$, 0.55 Cl, 2.11 ign. = 99.85. In some varieties there is 16.88 $ZrO_2$. Occurs in nephelite-syenite in Greenland, Norway, and Finland.

$Na_2Ca_3((Si,Zr,Ti)O_3)_4$. ROSENBUSCHITE. A rare metasilicate containing about 31.5 $SiO_2$, 19.0 $ZrO_2$, 7 $TiO_2$, with considerable CaO, $Na_2O$, and small amounts of the cerium metals, iron, manganese, and fluorine, occurring sparingly in nephelite-syenite in Norway and elsewhere.

$(Na_4,Ca_2,Mn_2,Zr)((Si,Zr)O_3)_2$. LÅVENITE. 29.17 $SiO_2$, 28.90 $ZrO_2$, 2.00 $TiO_2$, 4.13 $(Ta,(Cb))_2O_5$, 0.78 $Fe_2O_3$, 3.02 FeO, 7.30 MnO, 6.93 CaO, 11.23 $Na_2O$, 3.82 F, 0.65 $H_2O$, zircon 3.08 = 101.01. Occurs sparingly in nephelite-syenite in Norway and elsewhere.

12 $(Na_2,Ca)(Si,Zr)O_3 \cdot RCb_2O_6$. WÖHLERITE. 30.12 $SiO_2$, 16.11 $ZrO_2$, 0.42 $TiO_2$, 12.85 $Cb_2O_5$, 0.66 $Ce_2O_3$, 0.48 $Fe_2O_3$, 1.26 FeO, 1.00 MnO,

26.95 CaO, 0.12 MgO, 7.50 $Na_2O$, 0.74 $H_2O$, 2.98 F = 101.19 less 1.24 O for F = 99.95. Occurs like låvenite in nephelite-syenite in Norway.

$(Na_2,Ca)(Si,Zr)O_3$. HJORTDAHLITE with fluorine present. 31.60 $SiO_2$, 1.50 $TiO_2$, 21.48 $ZrO_2$, 0.34 $Fe_2O_3$, 0.94 FeO, 0.96 MnO, 0.10 MgO, 32.53 CaO, 6.53 $Na_2O$, 0.58 $H_2O$, 5.83 F = 102.39 less 2.43 O for F = 99.96. A very rare mineral in nephelite-syenite on the Island of Middle Arö in the Langesund fjord, Norway.

Zirconium also occurs in the rare mineral hainite which crystallizes in phonolites in Bohemia. Traces of it are found in melanocerite, caryocerite, tritomite, silicates of the cerium and yttrium metals, which occur in nephelite-syenites in Norway.

In the titanosilicates, there are the following amounts: in astrophyllite from 1.0 to 5.0 $ZrO_2$; in johnstrupite, 2.84 $ZrO_2$; in mosandrite, 7.43 $ZrO_2$.

5 $RTiO_3 \cdot 5 RZrO_3 \cdot R(Cb,Ta)_2O_6$. POLYMIGNITE. A columbate and titanate (zirconate) of the cerium metals, iron, calcium, containing 29.71 $ZrO_2$ in one instance. Occurs in nephelite-syenite in Norway, and possibly elsewhere.

There is 1.97 $ZrO_2$ in ånnerödite, a pyrocolumbate of uranium and yttrium, with doubtful formula, occurring in granite pegmatite at Ånneröd, Norway. There is also a very little zirconium in the analyses of xenotime, yttrium phosphate; and 7.59 $ZrO_2$ in uraninite from Colorado.

**Ti. Titanium** resembles zirconium in being quadrivalent, and in forming weak bases or weak acids. It also enters some compounds isomorphously with zirconium and silicon. But it is more closely associated with silicon than zirconium is, and occurs in more pyrogenetic minerals, and is a commoner element in igneous rocks. It is combined with iron without silicon to a greater extent than it is with silicon. It also occurs as an oxide in rocks with quartz. It occurs in greatest amounts in rocks lowest in silicon and richest in iron.

$TiO_2$. RUTILE. As a pyrogenetic mineral rutile occurs in very small amounts widely disseminated in highly siliceous rocks, granites, usually crystallized within the quartz, $SiO_2$.

$FeTiO_3$. ILMENITE. 52.7 $TiO_2$, 47.3 FeO = 100, with variable composition, with diminution of $TiO_2$ grading into hematite $Fe_2O_3$. A common mineral in igneous rocks of nearly all kinds from the most siliceous to the least siliceous. Most abundant in the least siliceous rocks. There may be 3 or 4 per cent of $TiO_3$ in pyrogenetic magnetite.

$Fe_4(TiO_4)_3$. PSEUDOBROOKITE. 42.9 $TiO_2$, 57.1 $Fe_2O_3$ = 100. A rare mineral occurring in very small amounts in several kinds of volcanic rocks, andesite, trachyte, nephelinite.

$CaTiO_3$. PEROVSKITE. 58.9 $TiO_2$, 41.1 CaO = 100. A titanate of calcium occurring in igneous rocks very low in silicon, peridotites.

$CaTiSiO_5$. TITANITE. 30.6 $SiO_2$, 40.8 $TiO_2$, 28.6 CaO = 100. A titanosilicate of calcium, common in igneous rocks not too low in silicon, especially in calcic varieties.

GUARINITE, like titanite in composition, occurring in trachyte.

15 $CaTiSiO_5 \cdot (Al,Fe,Y)_2(SiTi)O_5$. KEILHAUITE. Titanosilicate similar to titanite but containing a small amount of aluminium, ferric iron, and the yttrium metals, with 27.0 $TiO_2$; occurring in syenite in Norway.

$\overset{I}{R}_4\overset{II}{R}_4Ti(SiO_4)_4$. ASTROPHYLLITE. An orthosilicate of iron, manganese, titanium, with alkalies and other elements. 35.23 $SiO_2$, 11.40 $TiO_2$, 1.21 $ZrO_2$, 0.34 $Ta_2O_5$, tr $Al_2O_3$, 3.73 $Fe_2O_3$, 29.02 FeO, 5.52 MnO, 0.13 MgO, 0.22 CaO, 3.63 $Na_2O$, 5.42 $K_2O$, 4.18 ign. = 100.03. A rare mineral occurring in nephelite-syenite pegmatite.

$\begin{bmatrix} F_6\overset{IV}{R}_3 \\ \overset{III}{FR} \end{bmatrix}(\overset{I}{R}_2)_4\overset{II}{R}_{13}\overset{II}{R}_3(SiO_4)_{12}$. JOHNSTRUPITE. A complex silicate of the cerium metals, calcium and sodium, with titanium and fluorine. It contains 7.57 $TiO_2$. MOSANDRITE, a similar mineral, contains from 5 to 9 per cent $TiO_2$. RINKITE, a similar compound, contains 13.36 $TiO_2$. These are rare minerals in nephelite-syenite pegmatites.

3 CaO $\cdot (Fe,Ti)_2O_3 \cdot$ 3 $(Si,Ti)O_2$. SCHORLOMITE. Probably a titaniferous garnet containing about 26.0 $TiO_2$; probably pyrogenetic in nephelite-syenite at Magnet Cove, Ark. A titaniferous garnet similar to it occurs in phonolite in the Kaiserstuhl. IVAARITE with 18.98 $TiO_2$ occurs in nephelite-syenite in Finland. There is from 1 to 8 per cent of $TiO_2$ in some andradite garnets, 3 CaO $\cdot Fe_2O_3 \cdot$ 3 $SiO_2$.

2 $Na_2O \cdot$ 9 FeO $\cdot AlFeO_3 \cdot$ 12 $(Si,Ti)O_2$. ÆNIGMATITE. A titanosilicate related to the amphiboles, containing about 7.57 $TiO_2$, occurring in sodalite-syenite in Greenland. A similar mineral, cossyrite, occurs in sodic lavas, pantellerite, on Pantellaria.

$CaR_3(SiO_3)_4$. AMPHIBOLE, in which R is chiefly magnesium, iron, and smaller amounts of aluminium, ferric iron, sodium, hydroxyl, fluorine, etc., with variable amounts of titanium, in some cases as much as 8.47 $TiO_2$, Linosa near Pantelleria.

6 $CaSiO_3 \cdot$ 2 $Na_2ZrO_2F_2 \cdot (Ti.SiO_3 \cdot TiO_3)$. ROSENBUSCHITE. A zirconosilicate related to pyroxene, with 7.59 $TiO_2$, occurring in nephelite-syenite pegmatite. There are smaller amounts of $TiO_2$ in the closely related minerals, *låvenite, wöhlerite, hiortdahlite*, having a similar occurrence.

$CaR(SiO_3)_2$. PYROXENE, in which R is chiefly magnesium, iron, aluminium, ferric iron, and small amounts of other elements. Titanium is present in some varieties up to as much as 4.57 $TiO_2$

$(H,K)_2$ $(Mg,Fe)_4$ $(Al,Fe)_2$ $(SiO_4)_4$ or $(H,K)_2$ $(Mg,Fe)_2$ $Al_2$ $(SiO_4)_3$. BIOTITE. There may be variable amounts of titanium in the iron-bearing micas, up to 4.73 $TiO_2$ in biotite at Miask, and 4.68 $TiO_2$ in lepidomelane from Langesund fjord, Norway.

There is a very small amount of titanium in some tourmalines, and in a few other pyrogenetic silicates.

$\overset{III}{R}(CbO_3)_3 \cdot 2\,\overset{III}{R}(TiO_3)_3 \cdot 3\,H_2O$. POLYCRASE. A columbate and titanate of yttrium, erbium, cerium, uranium, with about 29.0 $TiO_2$; a rare mineral which occurs in granite pegmatite.

(?)$\overset{III}{R}(CbO_3)_3 \cdot \overset{III}{R}_2(TiO_3)_3 \cdot 3/2\,H_2O$. EUXENITE. Like polycrase, containing small amounts of germanium, with from 20.0 to 30.0 $TiO_2$. Occurs in granite pegmatite.

$\overset{III}{R}_2Cb_4O_{13} \cdot \overset{III}{R}_2(Ti,Th)_5O_{13}$. ÆSCHYNITE. A columbate, titanate, and thorate of the cerium metals chiefly, with about 21.0 $TiO_2$, occurring in granite pegmatite.

$5\,RTiO_3 \cdot 5\,RZrO_3 \cdot R(Cb,Ta)_2O_6$. POLYMIGNITE. A columbate, titanate, and zirconate of the cerium metals, iron, calcium, with 18.90 $TiO_2$, occurring in nephelite-syenite pegmatite.

$RCb_2O_6 \cdot R\,(Ti,Th)O_3$. PYROCHLORE. A columbate, titanate, and thorate of calcium, cerium, with fluorine; contains from 5.0 to 13.0 $TiO_2$; occurs in nephelite-syenite in Norway. A small amount of titanium occurs in hatchettolite.

**Pb. Lead,** a member of this group of elements, is very rarely present in pyrogenetic minerals. In uraninite there is from 3.0 to 11.0 PbO. In the columbate, ånnerödite, there is 2.40 PbO; in fergusonite 1.94 PbO. The silicate thorite sometimes contains as much as 1.67 PbO.

**Sn. Tin** while quadrivalent and a member of Group IV is also bivalent in some compounds. It is not closely related to the other elements in this group, and is found but seldom in pyrogenetic minerals except in traces in association with the cerium metals, and in the columbates and tantalates.

$SnO_2$. CASSITERITE, the only pyrogenetic mineral in which tin plays a prominent rôle, occurs in some granites and their pegmatites.

**Si. Silicon** is next to oxygen the most abundant element in igneous rocks. It is quadrivalent, and is always an acid-forming element. The acids are not very strong, but the compounds are most of them very stable. While it has many resemblances to carbon, the two elements do not make compounds isomorphous with one another, and there is almost no carbon in igneous rocks. In general there is none noted in chemical analyses of fresh rocks. Owing to the fact that silicon enters the great majority of pyrogenetic minerals, most of which have been already noted, the list

of silicates will not be given with the formula of each, but the occurrence of silicon in the rock minerals will be stated in general terms.

$SiO_2$. QUARTZ and TRIDYMITE. The oxide, silica, crystallizes by itself as a pyrogenetic mineral in magmas rich in silicon, and in those low in silicon in which the base-forming elements are not sufficiently abundant to combine with all the silicon, or in which the basic character of some of them is not sufficiently strong to compel all the silicon to enter into combination with them. Thus quartz occurs in highly siliceous rocks, but does not occur in highly alkalic rocks with moderate content of silicon. It often occurs in less siliceous rocks low in alkalies, with considerable calcium, iron, and magnesium.

$\overset{\text{I}}{R}_2Si_2O_5$ or $\overset{\text{I}}{R}_4(Si_2O_5)_2$. DISILICATE, in which $\overset{\text{I}}{R}_4$ is replaced by (LiAl) — petalite, with 78.4 $SiO_2$, the only pyrogenetic disilicate. A rare mineral in granite pegmatite in a few localities.

$\overset{\text{I}}{R}_4Si_3O_8$. POLYSILICATE, in which $\overset{\text{I}}{R}_4$ is replaced by KAl, orthoclase, with 64.7 $SiO_2$; NaAl, albite, with 68.7 $SiO_2$. These are the only simple polysilicates among the pyrogenetic minerals.

$\overset{\text{I}}{R}_2SiO_3$. METASILICATE. Some of the commonest pyrogenetic minerals belong here. The list includes leucite, pollucite, enstatite, hypersthene, diopside, augite, ægirite, acmite, jadeite, spodumene, rosenbuschite, låvenite, wöhlerite, hjortdahlite, hornblende, riebeckite, arfvedsonite, ænigmatite, beryl, eudialyte (eucolite), catapleiite, cappelenite, melanocerite, caryocerite, tritomite, lepidolite.

INTERMEDIATE SILICATES, whose composition lies between that of the foregoing and orthosilicates. In this list may be included lime-soda-feldspars, which may be considered mixtures of polysilicates and orthosilicates; rock-making nephelite; leucophanite, meliphanite, cordierite, and possibly analcite.

$R_2SiO_4$. ORTHOSILICATE. Many of the commonest pyrogenetic minerals, as well as some less abundant or rare minerals. They include sodium-nephelite, cancrinite, sodalite, haüynite, noselite, helvite, danalite, garnets, schorlomite, olivine, fayalite, phenacite, melilite, zircon, thorite, topaz, homilite, gadolinite, yttrialite, epidote, allanite, muscovite, biotite, (?) lepidolite, in part.

SUBSILICATES, or silicates of uncertain formulæ which may properly be basic or acid metasilicates or orthosilicates. Among them are tourmaline and dumortierite.

Silicon also enters titanosilicates, including titanite, guarinite, keilhauite, astrophyllite, johnstrupite, mosandrite, rinkite.

C. **Carbon,** though closely analogous to silicon in some characters, is an extremely rare element in pyrogenetic mineral compounds. Uncombined with other elements in the form of diamond it occurs in association with minerals from granitic pegmatites, and also in serpentine altered from peridotite, in which rock it is probably pyrogenetic. As the oxide $CO_2$ it is known in gaseous and liquid form as microscopic inclusions in quartz, but how far it may be primary and how far secondary has not been determined. In the quartz at Branchville, Conn., it is probably primary. Carbonates, $CaCO_3$, calcite, possibly also magnesium and iron carbonates, are rarely observed in any manner which might be considered pyrogenetic. In some instances, however, calcite in small amount has been considered pyrogenetic. In certain nephelite-syenite in Canada it was undoubtedly present at the time of the crystallization of the magma. Carbon enters the silicate compound, cancrinite, $H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$, with about 6.3 $CO_2$, but this is not a common mineral, being developed only in certain nephelite-syenites.

### SUMMARY FOR GROUP IV

Silicon is the most important element of this group in igneous rocks, is next in abundance to oxygen, and forms numerous silicates, those of the highest order containing the most active base-forming elements. As an oxide, $SiO_2$, it is abundant in rocks in which there are insufficient base-forming elements to unite with it as silicate compounds; and occurs also in those having the weaker base-forming elements, Mg, Fe, in the lower silicate compounds, or, in the case of Fe sometimes, not combined with silicic acid.

Titanium is a constituent of numerous silicates, forms a few titanates, and is commonly present in the iron oxides and ferrates, with which it is most closely associated; and also separates as the oxide, $TiO_2$, from some magmas rich in silicon and relatively poor in the base-forming elements. Zirconium, somewhat like titanium, enters into silicates chiefly, either in the acid radical or the base. It is most abundant in the most alkalic feldspathic rocks, where it enters rare silicate compounds. Thorium and cerium are much rarer elements closely allied to zirconium in characters and occurrence. Lead, tin, and germanium are extremely rare as constituents of igneous rocks.

Carbon is rarely present as a constituent of unquestionably pyrogenetic minerals. Its presence in pyrogenetic calcite in nephelite-syenites in Ontario is probably the result of its absorption in the magma along its contact with limestone.

## GROUP V

TANTALUM, COLUMBIUM, and VANADIUM are pentavalent elements which form weak bases in some compounds and somewhat stronger acids in others. They are rare elements in igneous rocks, especially vanadium, which is closely related to phosphorus chemically. BISMUTH, ANTIMONY, and ARSENIC are seldom if ever found in igneous rocks. They are both pentavalent and trivalent. Bismuth is base-forming; antimony is both base-forming and acid-forming; while arsenic is chiefly acid-forming. They are very similar chemically to phosphorus and nitrogen.

PHOSPHORUS, which is widely distributed in small amounts in igneous rocks, has three valencies, penta-, tetra-, and trivalent. It is an acid-forming element. It forms a number of different acids. NITROGEN has the same valencies as phosphorus, and is wholly acid-forming. It is found in only one pyrogenetic mineral in very small amounts together with helium.

**Ta, Cb. Tantalum** and **columbium** (niobium) are pentavalent elements, capable of forming weak bases but usually occurring as columbates or tantalates. They are rare elements, usually occurring in granite pegmatites and to a less extent in syenite pegmatites.

$RCb_2O_6 \cdot R(Ti,Th)O_3 \cdot NaF$, also $R_2Cb_2O_7 \cdot R(Ti,Th)O_3 \cdot NaF$, etc. PYROCHLORE. Chiefly a columbate of the cerium metals, calcium and other metals, with titanium, thorium, and fluorine; having 47.13 to 58.27 $Cb_2O_5$. Occurs in nephelite-syenite in Norway and in the Ural.

$2\,R(Cb,Ta)_2O_6 \cdot R_2(Cb,Ta)_2O_7$. HATCHETTOLITE. A tantalocolumbate of uranium, with less calcium and iron; having about 29.83 $Ta_2O_5$ and 34.24 $Cb_2O_5$. Occurs in granite pegmatite in Mitchell County, N. C.

$Ca_2Ta_2O_7$ pt. MICROLITE. Calcium pyrotantalate with columbium, fluorine, and a variety of metals in small amounts. About 68.43 $Ta_2O_5$, 7.74 $Nb_2O_5$. Occurs in granite pegmatite in several localities.

$(Y,Er,Ce)(Cb,Ta)O_4$. FERGUSONITE. Metacolumbate and tantalate of yttrium, erbium, cerium, uranium, etc.; having about 46.0 $(Cb,Ta)_2O_5$. Occurs in granite pegmatite, especially in Llano County, Texas.

$ErCbO_4$. SIPYLITE. A columbate of erbium chiefly, with cerium metals, etc. About 47.0 $Cb_2O_5$. Occurs in granite (?) in Amherst County, Va.

$(Fe,Mn)(Cb,Ta)_2O_6$. Columbite and Tantalite. Varying in composition from nearly pure columbate, columbite, with 82.7 $Cb_2O_5$, to nearly pure tantalate, tantalite, with 86.1 $Ta_2O_5$. These are the commoner compounds, and occur rather widespread in granite pegmatites.

$Fe(Ta,Cb)_2O_6$. Tapiolite. 73.9 $Ta_2O_5$, 11.1 $Cb_2O_5$, 15.0 FeO = 100. A rare mineral occurring in granite pegmatite in Sukula, Finland.

$\overset{II}{R}\overset{III}{R}_2(Ta,Cb)_4O_{15} + 4\,H_2O$. Yttrotantalite. A tantalate and columbate of yttrium, iron, calcium, and other metals, having 46.25 $Ta_2O_5$, 12.32 $Cb_2O_5$. Occurs in granite pegmatite.

$\overset{II}{R}_3\overset{III}{R}_2(Cb,Ta)_6O_{21}$. Samarskite. $\overset{II}{R}$ = Fe and $UO_2$ chiefly; and $\overset{III}{R}$ = cerium and yttrium metals. About 41.0 $Cb_2O_5$, 14.0 $Ta_2O_5$. Occurs in granite pegmatite.

Annerödite. A pyrocolumbate of uranium and yttrium with other elements. About 48.13 $Cb_2O_5$. Occurs in granite pegmatite in Norway.

$4\,RO \cdot 3\,Ta_2O_5$? Hielmite. A stannotantalate (and columbate) of yttrium, iron, manganese, calcium; having about 54.52 $Ta_2O_5$, 16.35 $Cb_2O_5$; occurring in granite pegmatite in Sweden.

$\overset{III}{R}_2Cb_4O_{13} \cdot \overset{III}{R}_2(Ti,Th)_5O_{13}$. Æschynite. A columbate and titanate (thorate) of the cerium metals chiefly, with about 32.51 $Cb_2O_5$. Occurring in granite pegmatite.

$R((Cb,Ta)O_3)_2 \cdot 5\,\overset{III}{R}((Ti,Zr)O_3)_3$. Polymignite. A columbate and titanate (zirconate) of the cerium metals, iron, calcium, having 11.99 $Cb_2O_5$, 1.35 $Ta_2O_5$. Occurs in nephelite-syenite.

$\overset{III}{R}(CbO_3) \cdot \overset{III}{R}_2(TiO_3)_3 \cdot \frac{3}{2}\,H_2O$. Euxenite. $\overset{III}{R}$ = yttrium, erbium, cerium, and uranium, with about 35. $Cb_2O_5$. Occurs in granite pegmatite.

$\overset{III}{R}(CbO_3)_3 \cdot 2\,\overset{III}{R}(TiO_3)_3 \cdot 3\,H_2O$. Polycrase. Composition similar to that of euxenite. Occurs in granite pegmatite.

Columbium and tantalum also occur in small amounts in a few of the rarer silicates as follows: 11.58 to 14.47 $Cb_2O_5$ in wöhlerite; 5.20 $Ta_2O_5$ in låvenite; 3.52 $Ta_2O_5$ in eucolite; 3.65 $Ta_2O_5$ in melanocerite; 3.11 $Ta_2O_5$ in caryocerite; 3.09 $Ta_2O_5$ in tritomite. These minerals occur in nephelite-syenite.

V. **Vanadium** is an extremely rare element in igneous rocks, being found in traces in some rock analyses, but not being a notable constituent in any pyrogenetic rock mineral so far as known at present.

P. **Phosphorus** belongs to the same group as vanadium and the two elements just described, and in some compounds is isomorphous with vanadium, but it differs in most respects from these elements and enters different pyrogenetic compounds from those formed by columbium and tantalum. It is widely distributed in small amounts in nearly all igneous rocks,

chiefly as calcium fluophosphate; other pyrogenetic phosphates occur in pegmatites.

| | | |
|---|---|---|
| $(CaF)Ca_4(PO_4)_3$ | FLUOR-APATITE. | 42.3 $P_2O_5$, 55.5 CaO, 3.8 F = 101.6 |
| $(CaCl)Ca_4(PO_4)_3$ | CHLOR-APATITE. | 41.0 $P_2O_5$, 53.8 CaO, 6.8 Cl = 101.6. |

The fluor-apatites are the commoner, and occur in small amounts in nearly all igneous rocks.

$(Y,Ce,Er)PO_4$. XENOTIME. If all yttrium, then 38.6 $P_2O_5$, 61.4 $Y_2O_3$. Erbium may be present in large amount, also cerium, iron, silicon, and thorium. Occurs in granite pegmatite.

$(Ce,La,Di)PO_4$. MONAZITE. About 30. $P_2O_5$ at most; may contain small amounts of silicon and thorium. Occurs in granite pegmatite.

$Li(Fe,Mn)PO_4$. TRIPHYLITE and LITHIOPHILITE. About 45.0 $P_2O_5$. The relative amounts of iron and manganese vary from 45.5 FeO and no manganese in triphylite, to 45.1 MnO and no iron in lithophilite; there being 9.5 to 9.6 $Li_2O$ in each. Accompanies other lithium minerals in granite pegmatite.

$NaGlPO_4$. BERYLLONITE, with 55.9 $P_2O_5$, 19.7 GlO, 24.4 $Na_2O$ = 100. Occurs in granite pegmatite.

$(CaF)GlPO_4$. HERDERITE, with fluorine in part replaced by hydroxyl. If OH : F = 1 : 1, then 43.8 $P_2O_5$, 15.4 GlO, 34.6 CaO, 5.9 F, 2.8 $H_2O$ = 102.5 less 2.5 O for F = 100. Occurs in granite pegmatite.

$(RF)RPO_4$. TRIPLITE. R = Fe and Mn, also Ca and Mg, in variable proportions, with 30.0 to 35.0 $P_2O_5$. Occurs in granite pegmatites.

$(ROH)RPO_4$. TRIPLOIDITE. 32.0 $P_2O_5$, 16.2 FeO, 47.8 MnO, 4.0 $H_2O$ = 100. Occurs with triplite in granite pegmatite at Branchville, Conn.

$Li(AlF)PO_4$. AMBLYGONITE. 47.9 $P_2O_5$, 34.4 $Al_2O_3$, 10.1 $Li_2O$, 12.9 F = 105.3 less 5.3 O for F = 100. Occurs in granite pegmatite.

Several hydrous phosphates, dickinsonite, eosphorite, etc., which occur in granite pegmatites associated with anhydrous phosphates are probably secondary minerals.

**Nitrogen,** it is interesting to note, though abundantly present in the atmosphere, is not present in igneous rocks in notable amounts, nor does it enter into the composition of any pyrogenetic mineral except uraninite, in which it may be accompanied by helium as in the case of the granite pegmatite at Branchville, Conn. It is well known that nitrates are almost always easily soluble and therefore unstable compounds.

## GROUP VI

URANIUM, TUNGSTEN, and MOLYBDENUM are hexavalent and yield acid anhydrides, and enter acid radicals; uranium also forms bases, and is also tetravalent. They are rare elements in igneous rocks. CHROMIUM is hexavalent, also trivalent and bivalent; with the latter valencies it resembles and is sometimes isomorphous with iron. It yields an acid anhydride $CrO_3$ when hexavalent, and two basic hydroxides $Cr(OH)_2$ and $Cr(OH)_3$ when exhibiting other valencies.

TELLURIUM and SELENIUM have not yet been found in pyrogenetic minerals. SULPHUR is present in small amounts in some rocks and in notable amounts in exceptional ones. It is sometimes hexavalent, but oftener bivalent; also trivalent, tetravalent, and heptavalent. Its oxides form strong acids. It is chemically somewhat analogous to oxygen, but is most like selenium and tellurium.

OXYGEN, the most abundant element in igneous rocks, is in most cases bivalent, and is an extremely active element, and enters into combination with most other elements. It forms an essential component of most acid radicals.

U. **Uranium**, a rare element having various valencies, is hexavalent in some compounds. It occurs very sparingly in igneous rocks, chiefly as uraninite, a uranate of uranyl, together with lead, thorium, zirconium, often with the cerium and yttrium metals. The proportions of $UO_3$ to $UO_2$ vary widely. There is generally over 80 per cent of uranium oxides, and from 3.0 to 11.0 PbO, and sometimes nitrogen and helium. Uraninite occurs in granite pegmatite.

Uranium enters into the composition of several columbium and tantalum minerals. There is about 15.5 $UO_3$ in hatchettolite; 19.47 $UO_3$ in polycrase; 16.28 UO in ånnerödite; 13.48 $UO_2$ in some samarskite; 12.12 $UO_2$ in euxenite; 4.87 $UO_2$ in hielmite; 8.16 $UO_3$ in some fergusonite; 3.47 UO in sipylite; 1.61 $UO_2$ in yttrotantalite; 1.59 $UO_3$ in microlite. Uranium also occurs in a variety of the silicate, thorite, which may contain as much as 9.78 $U_2O_3$, Arendal, Norway.

W. **Tungsten** is a still rarer element in igneous rocks than uranium. The only tungstate that may possibly be a pyrogenetic mineral in some granite pegmatites is scheelite, $CaWO_4$; 80.6 $WO_3$, 19.4 CaO = 100. Molybdenum may replace tungsten to some extent. Tungsten occurs in small amounts in a number of pyrogenetic columbates and tantalates, being most noticeable in yttrotantalate, with 2.36 $WO_3$. In these minerals it is usually associated with tin oxide, $SnO_2$, and there is generally less than one per cent of $WO_3$.

**Mo. Molybdenum** occurs in molybdenite, $MoS_2$, which is sometimes disseminated through granite, syenite, nephelite-syenite, and their pegmatites; and may possibly occur in another, scheelite, just mentioned.

**Cr. Chromium** is hexavalent in some compounds, but possesses other valencies, and is usually considered to be trivalent in the pyrogenetic minerals.

**S. Sulphur,** which is so intimately associated with volcanic eruptions, is not an abundant constituent of igneous rocks. It is widely distributed in small amounts as a sulphide, is present in several rather common silicates, but never occurs as a sulphate.

$FeS_2$. PYRITE, with 53.4 S, is very commonly present in small amounts in igneous rocks as a pyrogenetic compound.

$Fe_nS_{n+1}$. PYRRHOTITE, with about 39.0 S, is less common than pyrite, but occurs in considerable amounts in the less siliceous rocks with the following sulphides in certain localities:

$FeCuS_2$. CHALCOPYRITE, with about 35.0 S.

(Fe,Ni)S. PENTLANDITE, with about 36.0 S.

Sulphur is present in the silicates, haüynite and noselite, with from 7.30 to 13.25 $SO_3$; and in helvite and danalite, with about 5.0 S.

**O. Oxygen** is the most abundant element, and constitutes about 47 per cent of the average igneous rock. It enters nearly every chemical compound that forms pyrogenetic minerals, certainly all those present in any considerable amount. There are very small amounts of primary sulphides or fluorides in some igneous rocks, but sulphides are very abundant in exceptional cases. Still smaller amounts of native elements, such as gold, platinum, iron, and carbon in the form of diamond, are found as primary constituents of igneous rocks.

## GROUP VII

MANGANESE exhibits various valencies, the highest being heptavalent. In pyrogenetic compounds it is usually bivalent or trivalent and is isomorphous with iron. IODINE and BROMINE are not known as components of igneous rocks, but CHLORINE is sometimes present in small amounts. It is univalent in most compounds, but may be heptavalent in others. FLUORINE is a univalent element in most of its compounds; is one of the most active elements, and unites with every other element except oxygen. It occurs in small amounts in quite a number of pyrogenetic minerals, and is a prominent factor in many pneumatolytic processes.

**Cl. Chlorine** behaves as a univalent element in most of its compounds; it may under certain conditions be heptavalent. It is but sparingly present in igneous rocks, though a common accompaniment of volcanic eruptions. It enters only a few pyrogenetic minerals. There is 5.0 Cl in some Norwegian apatites, in most others there is less than 1.0 Cl. It enters into the composition of three pyrogenetic silicates: sodalite, with 1.7 Cl; a variable amount in noselite, usually less than 1 per cent; and eudialyte (eucolite), with as much as 1.7 Cl in some cases. There is sometimes a trace of chlorine in fluorite.

**F. Fluorine** is generally univalent like chlorine, but is more active, being more active than oxygen. It is present in very small amounts in many igneous rocks, in a few fluoride compounds, and in a number of silicates and other compounds as a fluorine radical.

$CaF_2$. FLUORITE. 48.9 F, 51.1 Ca = 100. Sparingly present as a pyrogenetic mineral in various igneous rocks, especially granite, syenite, and nephelite-syenite.

(Ce,La,Di)$F_3$. TYSONITE, with 29.44 F, occurs with feldspar, probably in granite pegmatite, in the Pikes Peak region, Colorado.

$R_2OF_4$ or $R_2O_3$.4 $RF_3$. FLUOCERITE, with 19.49 F, in which R = cerium metals chiefly, with some of the yttrium group, is closely related to tysonite, and occurs in granite pegmatite at Österby, Sweden.

$Na_3AlF_6$. CRYOLITE. 54.4 F, 12.8 Al, 32.8 Na = 100; occurs in granite at Ivigtut, Greenland. It also occurs in granite at the southern base of Pikes Peak, Colorado. Its pyrogenetic character is in doubt.

5 NaF.3 $AlF_3$. CHIOLITE. 57.7 F, 17.5 Al, 24.8 Na = 100; associated with cryolite in Greenland, and also in granite with cryolite near Miask, Ilmen Mountains.

Fluorine enters into the composition of numerous pyrogenetic silicates, chiefly those crystallized in pegmatites. It occurs in small amounts in some amphiboles, is more notable in the micas; there being as much as 1.26 F in some muscovite, variable amounts up to 4.0 F in biotite, and from 5.0 to 8.0 F in lepidolite. Fluorine is most notable in topaz with a possible maximum of 17.6 F. There is less than 1.0 F in tourmaline. In the rare pyroxenic minerals there are the following amounts: 5.83 in rosenbuschite; 5.83 in hjortdahlite; 3.82 in låvenite; 2.98 in wöhlerite. In the melanocerite group there is 5.78 F in melanocerite; 5.63 in caryocerite; 4.29 in tritomite. In the leucophanite group there is 7.9 F in leucophanite; 5.0 in meliphanite. In the titanosilicates there is 7.48 F in johnstrupite; 5.82 in rinkite; 2.57 in mosandrite. In the columbates and tantalates there is 3.75 F in pyrochlore; 2.85 in microlite; and less than 1.0 in fergusonite. In the phosphates there is 11.32 F in herderite; 11.26 in amblygonite; and 3.50 in fluor-apatite. Traces of fluorine are sometimes found in other pyrogenetic minerals

### GROUP VIII

Of the elements placed in this group there are three subgroups, two of which are scarcely represented among the constituents of igneous rocks. However, PLATINUM with OSMIUM, IRIDIUM, RHODIUM, RUTHENIUM, and PALLADIUM, occur in traces in mineral constituents of rocks low in silicon and rich in magnesium and iron, the peridotites. IRON is one of the most abundant elements, while COBALT and NICKEL occur in very small amounts in the rocks just mentioned, peridotites. These elements have been noticed in connection with elements of Group II.

**Occurrence of the Pyrogenetic Compounds.** — The elements and compounds just described occur in igneous rocks as solids in most cases; in a very few instances as liquids, and also as gases. Those that are solids are always crystallized. In a few cases they are uncombined elements, such as gold, diamond, metallic iron. There are some simple definite compounds without variableness in composition, such as $SiO_2$, quartz; $TiO_2$, rutile; $Al_2O_3$, corundum; $CaTiSiO_5$, titanite. But most of them have not a fixed composition because of the possibility of isomorphous mixture and of solid solutions; some of these are comparatively simple compounds, others are more or less complex. To the former belong $(Zr,(Th))SiO_4$, zircon; $(K,(Na))AlSi_3O_8$, orthoclase; $(Mg,Fe)_2SiO_4$, olivine; among the more complex are: $(H,K,)_2(Al,Fe)_2(Mg,Fe)_2(SiO_4)_3$, biotite; $KLi[Al(OH,F)_2]Al(SiO_3)$, lepidolite; $Ca(Mg,Fe,Mn,Na_2[Al,\overset{III}{Fe}(OH,F)])_3(SiO_3)_4$, hornblende.

There are few examples of polymorphism, as with $SiO_2$, quartz or tridymite; $CaTiSiO_5$, titanite or guarinite; possibly $TiO_2$, rutile, anatase, or brookite. Such differences as appear to exist in the crystallization of orthoclase and microcline, $KAlSi_3O_8$, are probably to be explained as the result of submicroscopic twining in the more symmetrical form, orthoclase. Polymorphic forms of some of the pyrogenetic compounds such as $CaSiO_3$ and $MgSiO_3$, which are known in laboratory products, are not commonly developed in the pyrogenetic minerals. Though it is possible that several forms of $MgSiO_3$ occur.

Compounds that are known to be isomorphous in laboratory

productions, or that are such in minerals developed in rocks of various kinds, are not always developed with equal frequency, or in some cases not at all, as pyrogenetic compounds. Thus $NaAlSiO_4$, sodium-nephelite; $KAlSiO_4$, kaliophilite; $LiAlSiO_4$, eucryptite, have like crystal symmetry and forms, and Na, K and Li in some instances enter compounds isomorphously, but only one compound — nephelite — occurs as a pyrogenetic mineral, and the potassium in it does not appear to be present as an orthosilicate, but as another silicate in solid solution. $(H,K)AlSiO_4$, muscovite; $(H,Na)AlSiO_4$, paragonite; $(H,Li)AlSiO_4$, lepidolite in part, are known as similar rock minerals, but the sodium compound is never pyrogenetic, and sodium seldom enters the pyrogenetic micas in notable amounts.

Compounds which are chemically similar, and might be expected to be isomorphous, have quite different crystal symmetry in some cases, such as $KAl(SiO_3)_2$, leucite; $NaAl(SiO_3)_2$, jadeite; $LiAl(SiO_3)_2$, spodumene. Again the sodium compound is not a common pyrogenetic mineral, if it occurs in this manner at all. On the other hand, of the compounds $KAlSi_3O_8$, microcline (orthoclase); $NaAlSi_3O_8$, albite; $LiAlSi_3O_8$ (unknown) the first two are isomorphous, and to some extent enter the same crystals, but the third is not known to occur in rocks. Finally, of the three possible corresponding disilicates only one, $LiAl(Si_2O_5)_2$, petalite, is known as a rock mineral. Similar observations might be made on the metasilicates of calcium, magnesium and iron, the pyroxenes and amphiboles, and also with regard to the orthosilicates of the same elements in the olivine group.

With respect to the various silicate compounds involving different silicic acids it is to be noted that orthosilicates, metasilicates, polysilicates, in very rare instances disilicates and uncombined silica may crystallize from the same rock liquid; and even elements that are base-forming under some conditions may separate from magmas containing uncombined silica. Thus mica, amphibole, orthoclase, quartz and magnetite or hematite, often occur in association in igneous rocks. It not infrequently happens that the orthosilicate, olivine, and quartz crystallize from the same magma. But it does not happen that the orthosilicate, nephelite, and quartz crystallize together.

Moreover, some base-forming elements commonly combine with several silicic acids, while others have a more restricted range. Thus the alkalies occur in polysilicates, metasilicates and orthosilicates, and lithium even in a disilicate; calcium, magnesium and iron in metasilicates and orthosilicates.

It is known that a molten magma of intermediate composition may crystallize into one combination of minerals under one set of physical conditions, and into another combination of minerals under another, which follows from the fact that the same elements enter numerous mineral compounds, and also that silicic acids of different kinds may be developed under different conditions. It is also well known that certain minerals are frequently associated together, others seldom, if ever.

All of these observations and many other facts that might be mentioned properly raise questions as to why each should occur, and what is known as to the conditions that may control the production of one or another mineral compound; the order in which they may separate from the liquid magma; and the shapes or forms of the different kinds of crystals. Answers to such questions may be found in part in the discussion of the chemical and physical characters of liquid magmas, and of the compounds that may crystallize from them, which forms the subject of succeeding chapters.

# CHAPTER III

## PRINCIPLES OF PHYSICS AND CHEMISTRY APPLICABLE TO ROCK MAGMAS

**Introduction.** — The evidences that what are known as igneous rocks were once liquid magmas with more or less fluidity are manifold. Molten lavas may be observed flowing from volcanic craters or from fissures, and upon cooling are found to be composed of crystals usually with some amorphous rock glass. In some instances the rock is almost wholly glass, as with certain pumices and obsidians. Many igneous rocks whose eruption was not witnessed, or that did not reach the surface of the earth at the time of their eruption, are found to contain glass, and their once molten condition is in this way indicated. Moreover, there may be evidences of their once highly heated and fluid condition in the fusing or baking of adjacent rocks along their contact, or in other signs of thermometamorphism; and in the shapes of their masses and their position with respect to the rocks through which they have been erupted. And while the position and arrangement of some of the crystals may in certain cases prove that they were transported in a flowing liquid, in other instances they demonstrate with equal clearness that all of the crystals were formed after the fluid magma came to rest, and that the rock magma at that time was wholly liquid. And though some rocks may be wholly crystalline, without vestige of glass, their correspondence in all other respects to rocks containing glass proves conclusively that such rocks were originally in a molten condition.

Experimental proof to the same effect has been furnished by the researches of James Hall[1] of Edinburgh in 1797, and those of Gregory Watt[2] in 1804, and more recently by the investi-

[1] Hall, James. Experiments on Whinstone and Lava (1798). Trans. Roy. Soc. Edinburgh, vol. 5, 1805, pp. 43–76.

[2] Watt, Gregory. Observations on Basalt and on the Transition from the Vitreous to the Stony Texture, etc. Phil. Trans. Roy. Soc. London, 1804, p. 179.

gations of Daubrée,[1] and of Fouqué and Michel-Lévy,[2] of Morozewicz[3] and others, all of whom succeeded in producing crystalline masses similar to certain kinds of igneous rocks by the simple cooling of fused magmas of the requisite chemical composition.

At one time the physical character of molten rock magmas was in dispute, and the possibility of a rock like granite ever having been a molten liquid was denied by some. But in 1861 Bunsen[4] pointed out the correspondence between liquid rock magmas and solutions of salts, calling attention to the fact that the order of crystallization of the minerals in granite is not in accord with their fusibility, and that their order of separation from the magma upon cooling is what it should be if they were in solution in one another and obeyed the laws governing the solution of salts. He remarks that "no chemist would think of assuming that a solution ceases to be a solution when it is heated to 200, 300 or 400 degrees, or when it reaches a temperature at which it begins to glow, or to be a molten fluid." Schott[5] considered molten glasses as supersaturated solutions analogous to salt solutions, and Lagorio[6] has assumed that a molten rock magma is nothing more than a solution of different silicates and other compounds. It is now universally believed that rock magmas are solutions of various compounds at high temperatures which may behave in a manner similar to solutions of other compounds at lower temperatures, whose physical and chemical characters may be more easily investigated.

The researches by Vogt[7] upon furnace slags, which in many respects are analogous to rock magmas; the work of Doelter[8] and his assistants upon the behavior of silicate mixtures, and the

[1] Daubrée, A. Études synthétiques de géologie expérimentale. Paris, 1879, p. 517.

[2] Fouqué, F., and Michel-Lévy, A. Synthèse des mineraux et des roches. Paris, 1882.

[3] Morozewicz, J. Tscher. min. petr. Mitth., vol. 18, pp. 1–90, and 105–240, 1898.

[4] Bunsen, R. Zeitschr. deutsch. geol. Gesell., vol. 13, 1861, p. 62.

[5] Schott, Poggendorff Annalen, vol. 154, p. 422.

[6] Lagorio, A. Tscher. min. petr. Mitth., vol. 8, 1887, p. 437.

[7] Vogt, J. H. L. Die Silikatschmelzlösungen, etc. Videnskabs-Selskabets Skrifter, I Math.-naturv. Klasse, 1903, No. 8; and 1904, No. 1.

[8] Doelter, C. Numerous publications in Neues Jahrb. Min. Petr., etc., and in Tscher. min. petr. Mitth.

more exact investigations of Day[1] and his colleagues upon the character and production of silicate minerals, have thrown much light upon the subject of the physical nature of liquid rock magmas and of their solidification to rocks. But the difficulties attending the investigation of silicate solutions at high temperatures, especially at pressures corresponding to those under which the crystallization of many rock magmas has taken place, and with the content of gases known to exist in them, render it necessary for us to derive our conceptions of the possible molecular constitution of the magmas, and of the laws controlling their crystallization, from the investigations and theories concerning solutions of other compounds that are liquid at lower temperatures. In order to obtain a reasonable understanding of the crystallization and solidification of rock magmas and therefore of the mineral and textural characters of igneous rocks, it will be advisable to review somewhat thoroughly certain principles affecting the physical chemistry of solutions and of their crystallization.

## KINETIC THEORY OF GASES AND LIQUIDS

The behavior of gases toward changes of temperature, pressure and volume, the diffusion of liquids in one another, and even of solids in solids, has led to the conception of gases, liquids, and solids being composed of particles, or molecules, which are in constant motion at all temperatures above absolute zero, a temperature at which such motion would cease. In gases the assumption is that the molecules are continually moving in all directions in straight lines, at a high velocity, and almost independently of one another. The impact of the molecules against one another and the walls of a containing vessel produces the PRESSURE which the gas exerts, or under which it exists. The cohesion of the molecules is a negligible quantity as compared with the kinetic energy of the molecules in the case of dilute gases, but becomes a qualifying factor when the gas is under greater pressure and is denser.

In liquids the cohesion plays a greater rôle than in gases, as is shown by the cohesion of the particles to form a drop, and in what is known as surface tension. But it is not sufficient to hold

[1] Day, A. L., *et alia*. Numerous publications in Am. Jour. Sci. and in Publications of the Carnegie Institution, Washington.

together all the molecules, some of which escape as vapor from liquids at various temperatures. If the escaping molecules are retained in a closed space there is a limit to the amount of vapor that may escape from a given liquid at a given temperature and pressure. The molecules leaving the liquid move about within the space, and those striking the surface of the liquid have as much chance of adhering to it as those trying to escape have of separating themselves from it. When as many return to it as leave it EQUILIBRIUM of action is established.

The pressure that exists when there is equilibrium between the liquid and vapor is the VAPOR TENSION of the liquid. When the temperature of the liquid is raised the kinetic energy of the molecules is increased, more can escape from the influence of the cohesion, the vapor tension of the liquid is raised. If the vapor from a liquid is removed, there eventually results complete evaporation of the volatilizing liquid. Liquids differ greatly in the degree to which they vaporize at different temperatures. Compare ether and mercury.

**Boiling Point.** — When the pressure of the vapor upon a liquid is equal to the vapor tension of the liquid for a particular temperature there is equilibrium of action as already said, and there is no loss of volume of the liquid by evaporation. With less and less vapor pressure on the liquid there is more and more evaporation, and if there were no pressure, or a perfect vacuum above the liquid, the liquid would pass rapidly into vapor with ebullition at any temperature. The act of passing into vapor with ebullition is called *boiling*, and the temperature at which it takes place in each kind of liquid under pressure is the *boiling point*. For any liquid the temperature at which boiling takes place increases with increase of pressure. The relation between boiling point and pressure follows no definite law, but must be established empirically for each kind of liquid.

**Critical Temperature** and **Critical Pressure.** —When a given volume of gas is heated in a closed vessel so that the volume remains constant, the increased kinetic energy of the molecules shows itself in increased pressure against the walls of the vessel, or if the gas is to be kept at constant pressure its volume must be increased. Hence if a given volume of gas is acted on by a pressure applied mechanically there would be a diminution in the volume unless a sufficient amount of heat were imparted to it to render the vapor tension equal to the pressure mechanically applied. Thus it is seen that an increase of heat and an increase

of pressure operate in opposite directions upon a gaseous body. And since a rise of temperature may cause a liquid to pass into a gaseous state it may be assumed at first that by increasing pressure a gas may be converted into a liquid. In many instances this is the case. Water vapor at ordinary temperatures under increasing pressure becomes denser, and when the pressure exceeds the vapor tension of water, for the temperature and pressure, condensation of the vapor to water sets in. But there is a temperature above which pressure will not cause liquefaction of water vapor, and at this temperature water will become vapor at any pressure. For water this temperature is 358° C. It is called the CRITICAL TEMPERATURE of a liquid or gas. The pressure which will just liquefy a gas at its critical temperature is the CRITICAL PRESSURE. The density of the liquid at this temperature and pressure is the same as that of the gas, and is called the CRITICAL DENSITY. Above the critical point under any pressure the substance behaves as a gas and not as a liquid. The term *vapor* is commonly applied to a gas below its critical temperature, when it can exist in contact with its liquid form, and when sufficiently compressed or cooled will condense to a liquid.

When carbon dioxide gas above its critical temperature is subjected to a pressure considerably above its critical pressure there is such a decrease in volume, that its density must be greater than that of liquid carbon dioxide at the same pressure at a temperature somewhat below its critical temperature. The critical pressure for water is 195 atmospheres approximately. At greater pressure and at temperatures above 358° C. the density of water gas must be greater than that of water at the same pressure, somewhat below its critical temperature. The critical density of water or of its gas at critical temperature and pressure is 0.429, when water at 4° C. is taken as unity.[1]

[1] The following data have been determined for water at the critical point:

| $\theta$ | $\pi$ | $\phi$ | $\delta$ | |
|---|---|---|---|---|
| 370.0 | 195.5 | — | — | Strauss |
| 358.1 | — | 0.001874 | 0.429 | Nadejdine |
| 365.0 | 200.5 | — | — | Cailletat and Mathias |
| 364.3 | 194.61 | 0.003864 | — | Battelli |

$\theta$ = temperature in ordinary centigrade. $\pi$ = vapor pressure at $\theta$ degrees temperature. $\phi$ = critical volume in terms of the theoretical volume of the gas or vapor at 0° C. under a pressure of one atmosphere. $\delta$ = density at $\theta$ degrees, water at 4° C. being taken = 1. Physico-Chemical Tables, John Castell Evans.

### KINETIC THEORY OF SOLIDS

In solids the effect of cohesive forces in the molecules is still more apparent than in liquids. It requires much more force to move the molecules over one another in many cases. But since there is a transition from highly viscous liquids to plastic solids, and since many solids are known to vaporize without passing into the liquid state, and since solids may diffuse through solids, there must be a similar state of motion among the particles or molecules of a solid as in those of liquids. There is, however, much less kinetic energy in the molecules and greater effectiveness of the molecular cohesion. When a solid is heated the kinetic energy of the molecules is increased, the effect of cohesive forces becomes relatively less, the tendency of the molecules to separate from the solid increases. All solids possess a vapor tension, which at ordinary temperatures may be almost negligible, but at high temperatures, approaching their melting point, become considerable, as in the case of platinum. Generally at some given temperature and pressure the kinetic energy is sufficient to overcome the cohesion characteristic of the solid and the substance passes from the solid to the liquid condition. This is the melting point.

**Change of State.** — A change of state, from gas to liquid and solid, or the reverse, involves either an absorption or a liberation of energy. In most instances a change from one state to another is accompanied by a marked difference in mobility of the molecules of the substance. In such cases the energy absorbed or liberated is an appreciable quantity, often considerable; and when it is expressed, or measured, in units of heat the temperature at which the change takes place for given pressure is definitely determinable. But when there is no marked difference between one state and another, as when a solid upon increasing temperature passes through imperceptible gradations from a slightly plastic solid to an equally viscous liquid, there is no appreciable quantity of heat absorbed at any particular temperature, and consequently no definite melting point.

**Amorphous and Crystallized Matter.** — There are notable distinctions between crystallized and uncrystallized matter which it is necessary to point out in connection with the discussion of

the possible states of matter and the use of the term SOLID. The orderly arrangement of molecules characterizing a crystal constitutes a definite phase, or state, of matter, which is distinguishable from an amorphous, or uncrystallized, state of the same substance or compound, and also from another crystallized state of the same substance having a different molecular arrangement. Thus quartz is a phase of silica distinct from silica glass, and distinct from tridymite. Each of these phases of silica may be described as a solid.

There are crystals, of organic compounds, so plastic that they cannot be called solids, but resemble highly viscous liquids. While other crystallized material is so mobile as to be called fluid crystals.[1] Each of these cases of crystallized matter constitutes a phase distinct from the uncrystallized, physically isotropic, condition of the same substance. And for this reason, matter has been classed as either physically isotropic, or as anisotropic. The first includes gases, liquids and uncrystallized solid matter, which is described as AMORPHOUS. The second includes all crystallized matter.

As already said, the passage from one state, or phase, of a substance to another, is accompanied in most cases by a marked absorption or liberation of energy, measurable as heat. And this can be recognized upon the passage of liquid to crystal, of amorphous solid (glass) to crystal, and of one crystal form to another, polymorphic, form. It is recognized in the transition between gas and liquid. But there is no recognizable point at which a definite amount of energy is liberated or absorbed when a liquid passes into an amorphous solid form of the same composition. In other words, judged by this criterion, an amorphous solid (glass) is not a phase, or state, of matter definitely distinguishable from a liquid of the same composition, for there are gradual transitions from one to the other in all their physical properties. There is an uninterrupted series of changes in each physical property, such as volume, density, optical refraction, thermal capacity, and viscosity. A glass then is a highly viscous liquid. The use of the term solid in connection with the discussion of equilibria between the phases of matter is misleading, unless it is understood to apply wholly to crystals.

[1] Lehmann, O. Flüssige Kristale, Leipzig, 1904.

There are cases, however, in which the transition from crystalline to amorphous state is accompanied by so slight an absorption of energy as not to be recognizable by ordinary methods of observation. Such a case is found in albite and microcline feldspar.[1] Long, thin, cleaved prisms of these feldspars placed across the top of platinum crucibles and heated for 3 hours at 1225° C. were converted into isotropic glass without change of shape or any sign of bending under their own weight. Rods of these feldspars heated for a few moments to temperatures from 1200 to 1300 degrees when weighted by platinum bent slightly. And upon optical examination it was found that the feldspar was only partly changed to isotropic glass, and that the glass and feldspar crystal had bent alike, and there were no signs of the glass having been more plastic than the crystal parts, or having been pressed out from between the crystal parts during the bending of the rods.

**Heat of Liquefaction and Vaporization.** — In most cases heat is absorbed upon the passage of a body from crystal to liquid phase, and also in passing from liquid to gas. This is known as HEAT OF LIQUEFACTION or OF VAPORIZATION. Upon the passage of a substance from a rarer to a denser phase heat is liberated. The amount of heat involved in any transformation is characteristic of each substance.

**Specific Heat.** — Since all the heat imparted to a substance does not appear as increase in temperature, but is partly converted into other forms of energy, the amount of heat required to raise the temperature one degree is another physical property characteristic of different substances. It is known as SPECIFIC HEAT and is expressed by the ratio between the amount of heat energy required to raise a given mass of any substance one degree, and the amount required to raise an equal mass of water one degree. In general, the lighter the molecules composing a substance the greater its specific heat, since the specific heat of an element varies inversely as its atomic weight.

**Melting Point and Pressure.** — When there is expansion of a substance upon passing from a crystal to a liquid condition, any pressure upon the substance would necessitate the expenditure of energy to overcome it. Increased pressure would require increased energy to overcome it. That is, increased heat would be required to produce liquefaction. The melting point of such substances is raised by increased pressure. When substances contract upon melting, as is the case with ice, pressure lowers

[1] Day, A. L. and Allen, E. T. Carnegie Institution of Washington, Publication 31. Washington, 1905, p. 51.

the melting point since it aids condensation. Unless otherwise stated, melting temperatures are to be understood as those at atmospheric pressures.

Since there is no definite point at which an amorphous solid, or glass, changes to a liquid, rock glasses can have no melting point, strictly speaking; and there can be no temperature at which a sudden change of volume will take place upon passing from liquid to solid glass.[1] All silicate minerals so far investigated probably expand upon melting; their melting points are therefore raised with increased pressure.

**Determination of Melting Points at High Temperatures.** — Temperature is usually defined in terms of the expansion of gas, but the difficulty of measuring the expansion of a gas at temperatures in the neighborhood of 1000° C., is so great, although the highest trustworthy temperature recorded in this manner is 1600 degrees,[2] that the thermoelectric current set up between platinum and an alloy of platinum and rhodium is used for most measurements of high temperatures. A thermoelectric couple of this character encased in a slender porcelain tube inside of platinum is inserted in the substance within a crucible placed in an electric furnace.[3]

A much less accurate method of procedure consists in heating small fragments of a substance on a strip of platinum foil by means of an electric current and noting the temperature by means of the linear expansion of the platinum. This is Joly's meldometer.[4] A crude approximation to the temperature of melting has been made by heating the substance by the side of small cones of mixtures prepared to melt at certain fixed temperatures and comparing the fusion of the substance with that of the prepared mineral mixtures.[5]

In the earlier, and in some of the latest, investigations of the melting points of rock minerals and glasses the moment of melt-

[1] The definite contraction attributed to basalt glass by Barus in Bulletin 103 of the U. S. Geological Survey, must have been due to a change of volume in the containing vessel, or to some other experimental condition at the time of solidification of the material under investigation.

[2] Holborn and Valentiner. Ann. der Physik, vol. 22, 1907, p. 1, and Day and Clement, Am. Jour. Sci., vol. 26, 1908, pp. 405–463.

[3] Day and Allen. Carnegie Institution of Washington, Publication No. 31, p. 15, et seq.

[4] Joly, J. Proc. Royal Irish Acad., vol. 3, 2, 1891, p. 38.

[5] Doelter, C. Tscher. min. petr. Mitth. vol. 20, part 3, 1901, p. 200, and Schertel, Berg u. Hütten männische Zeitung, 1880, also Brun, A., Arch. sci. phys. nat. 4th Ser., vol. 13, 1902, p. 552; vol. 18, 1904, p. 537.

ing has been determined by observing the rounding of corners or edges of the solid, or by noting the moment at which fluidity sets in. But as these phenomena are in many cases not distinctly marked, and it is not possible to determine the moment when change of shape or fluidity take place, such a method of determining melting point is inaccurate and involves a large personal equation, depending on the observer. This indefiniteness is obviated in many cases by judging of the melting point by noting the temperature at which an absorption of heat is recorded by the maintenance of a constant temperature in the substance during the changing temperature within the furnace. When there is a definite absorption of heat at some point in the rising temperature a change of state from solid to liquid, or a transition from one crystal structure to another is plainly indicated. But it has been found that in some rock minerals, such as albite, orthoclase and others, there is no indication that at any particular temperature a measurable amount of heat is absorbed; so it is not possible, therefore, to locate a melting point in such crystals.

SINTERING. When small fragments, or powder, of crystals or glass are heated for some time at temperatures somewhat below the melting point of the substance particles of the powder weld together to a more or less continuous, compact mass. This is called *sintering*. Powdered glass sinters more readily than powdered crystals of the same compound, and sometimes at temperatures several hundred degrees below the melting point of the crystal. The temperature at which sintering begins is lower the finer the powder. In viscous glasses, such as those of albite or orthoclase, long continued heating at comparatively low temperatures produces a perfectly continuous mass, the surface of which tends toward a minimum, so that Day concludes that "the sintering of powdered glasses is due to flow in the 'undercooled' liquid and is a phenomenon of viscosity and surface tension."[1] This is equally true of particles of mineral crystals, which become rounded upon sintering without loss of crystalline structure; indicating that when the particles are small enough, and rigidity is reduced, surface tension may overcome the rigidity of crystalline aggregation; a fact well illustrated in the extreme case of liquid crystals. According to Day all feldspar glasses sinter readily between 700° and 900° C., depending on the time and the fineness of the powder. In the case of powdered crystals of feldspar sintering takes place slowly at about 150 degrees below the melting point, but no definite sintering point for any substance can be located. Sintered fragments of crystal retain their crystalline character and do not become amorphous, that is, glass.

[1] Day and Allen, op. cit., p. 59.

It will be shown in another connection that Barus established the possibility of ionic diffusion in silicate glasses at temperatures considerably below the melting point, or the temperature at which there is a change in their shape which is recognised as melting, indicating molecular mobility in such substances while they may be said to be solid.

**Melting Points of Rock Minerals.** — The following observations of the melting points of the minerals commonly crystallized from molten magmas have been made by several methods, and represent varying degrees of accuracy. The most reliable are placed first, and have been determined by the thermoelectric methods used by Day. The next series was made by Doelter, using a thermoelectric element to determine the temperature and noting the moment when fusion rounded the corners or edges of crystal fragments. The third series of determinations was made by Joly and Cusack on a meldometer. Minerals with the highest melting points are placed first in the list.

MELTING POINTS OF PYROGENETIC MINERALS

| | Day and others.[1] | Doelter,[2] pyrometer, 1903. | Joly and Cusack,[3] meldometer. Rapid heating. |
|---|---|---|---|
| Corundum (W. Hempel), 1865° .... | ........... | ........... | ........... |
| Zircon.. ........................ | ........... | ........... | 1760 ap. |
| Tridymite........................ | 1625 | ........... | ........... |
| Rutile........................... | ........... | ........... | 1560 |
| Anorthite, natural............... | ........... | 1170–1190 | ........... |
| An } Artificial......... | 1532 | ........... | ........... |
| $n_8$ | 1500 | ........... | ........... |
| $n_3$ | 1463 | labradorite 1155–1180 | labradorite 1230 |
| $n_1$ | 1419 | ........... | ........... |
| $n_1$ | 1367 | ........... | ........... |
| $n_1$ | 1340 ap. | ........... | ........... |
| | 1230 est. | ........... | ........... |

[1] Day, A. L., Allen, E. T., and others. Am. Jour. Sci., 4th Ser., vol. 19, 1905, p. 93; vol. 21, 1906, p. 100; vol. 22, 1906, p. 265, and p. 385; and in publications of the Carnegie Institution.

[2] Doelter, C. Beziehungen zwischen Schmelzpunkt und chemischer Zusammensetzung der Mineralien. Tscher. min. petr. Mitth., vol. 22, 1903, pp. 297–321.

[3] Joly, J. Proc. Royal Irish Acad., Ser. III, vol 2, 1891, and Congr. géol. intern., VIII, Paris, 1900.
Cusack, R. *Ibid*, vol. 4, 1896.

MELTING POINTS OF PYROGENETIC MINERALS — *Continued*

| | | Day and others.[1] | Doelter,[2] pyrometer, 1903. | Joly and Cusack,[3] meldometer. Rapid heating. |
|---|---|---|---|---|
| | Albite, natural | ........ | 1120 | 1172–1175 |
| | Orthoclase, Arendal | ........ | 1190 | ........ |
| | Adular, Gotthard | ........ | 1185–1190 | 1165–1175 |
| | Sanidine, Drachenfels | ........ | 1140–1150 | 1140 |
| | Microcline, Pikes Peak | ........ | 1150–1160 | 1169–1175 |
| | Leucite | ........ | 1275–1280 | 1298 |
| | Nephelite, Vesuvius | ........ | 1110 | 1059–1070 |
| | Norway | ........ | 1090–1100 | 1070 |
| | Haüynite, Vesuvius | ........ | 1190–1195 | ........ |
| | Sodalite | ........ | 1030 | 1130 |
| | Analcite | ........ | 880–890 | ........ |
| Mica | Phlogopite, Ceylon | ........ | 1290 | ........ |
| Mica | Burgess | ........ | 1250–1255 | ........ |
| Mica | Lepidomelane from tonalite | ........ | 1130–1135 | ........ |
| Mica | Meroxene, Vesuvius | ........ | 1230–1240 | ........ |
| Mica | Biotite, Vesuvius | ........ | 1155–1160 | ........ |
| Mica | Muscovite, New Hampshire and Middletown | ........ | 1255–1260 | ........ |
| Mica | Lepidolite, Rozena | ........ | 925 | ........ |
| Mica | Zinnwaldite — Zinnwald, light | ........ | 940–950 | ........ |
| | Pyrope, Merouitz | ........ | 1185 | ........ |
| | Grossularite, Monzoni | ........ | 1125–1130 | ........ |
| | Almandite, Traversella | ........ | 1110–1115 | 1265 |
| | Melanite, Frascati | ........ | 925–935 | ........ |
| | Epidote | ........ | ........ | 965 |
| $R_2SiO_4$ | $Ca_2SiO_4$ | 2082 | ........ | ........ |
| $R_2SiO_4$ | Monticellite, Monte Somma | ........ | 1400–1410 | ........ |
| $R_2SiO_4$ | Forsterite, Sardinia | ........ | >1460 | ........ |
| $R_2SiO_4$ | Olivine, gem, Egypt | ........ | 1390–1395 | ........ |
| $R_2SiO_4$ | Vesuvius | ........ | ........ | 1363–1378 |
| $R_2SiO_4$ | Lipari, 8.45 FeO | ........ | 1265–1275 | ........ |
| $R_2SiO_4$ | Hyalosiderite, Sasbach, 29.96 FeO | ........ | 1215–1220 | ........ |
| $R_2SiO_4$ | Hortonolite, 44.37 FeO | ........ | 1175–1180 | ........ |
| $R_2SiO_4$ | Fayalite, 66.01 FeO | ........ | 1055 | ........ |
| | $MgSiO_3$, monoclinic | 1521 | ........ | ........ |
| | $CaSiO_3$, monoclinic | 1512 | ........ | ........ |
| | $CaMg(SiO_3)_2$, monoclinic | 1380 | ........ | ........ |
| | Enstatite, Bamle | ........ | 1375–1380 | ........ |
| | Bronzite, Kraubath | ........ | 1330–1350 | ........ |
| | Bronzite | ........ | ........ | 1295, 1300 |
| | Hypersthene, St. Paul | ........ | 1185–1195 | ........ |

[1] Day, A. L., Allen, E. T., and others. Am. Jour. Sci., 4th Ser., vol. 19, 1905, p. 93; vol. 21, 1906, p. 100; vol. 22, 1906, p. 265, and p. 385; and in publications of the Carnegie Institution.

[2] Doelter, C. Beziehungen zwischen Schmelzpunkt und chemischer Zusammensetzung der Mineralien. Tscher. min. petr. Mitth., vol. 22, 1903, pp. 297–321.

[3] Joly, J. Proc. Royal Irish Acad., Ser. III., vol. 2, 1891, and Congr. géol. intern., VIII, Paris, 1900.
Cusack, R. *Ibid*, vol. 4, 1896.

MELTING POINTS OF PYROGENETIC MINERALS — *Concluded*

| | Day and others.[1] | Doelter,[2] pyrometer, 1903. | Joly and Cusack,[3] meldometer. Rapid heating. |
|---|---|---|---|
| Malacolite, Rezbanya, 1.38 FeO | ............ | 1220 | |
| Diopside, Ala., 2.91 FeO | ............ | 1245–1250 | 1187–1195 |
| Nordmarken, 0.76 $Fe_2O_3$, 17.34 FeO | ............ | 1135–1140 | ............ |
| Hedenbergite, Dognaczka, 2.85 $Fe_2O_3$, 17.24 FeO | ............ | 1095 | ............ |
| Tunaberg, 0.10 $Fe_2O_3$, 26.29 FeO | ............ | 1090–1110 | ............ |
| Augite: | | | |
| Mti. Rossi, 3.85, $Fe_2O_3$, 7.89 FeO | ............ | 1165–1170 | ............ |
| Vesuvius, yellow, 1.09 $Fe_2O_3$, 6.78 FeO | ............ | 1175–1180 | ............ |
| black, 4.47 $Fe_2O_3$, 4.09 FeO | ............ | 1160–1170 | ............ |
| Vesuvius and elsewhere | | ............ | 1187–1199 |
| Arendal, green, 1.08 $Fe_2O_3$, 4.50 FeO | ............ | 1150 | ............ |
| black, 0.60 $Fe_2O_3$, 15.59 FeO | ............ | 1095–1110 | ............ |
| Spodumene, Stirling | ............ | 1080–1090 | 1173 |
| Jadeite, Tibet | ............ | 1000 | ............ |
| Ægirite, Langesund fjord | ............ | 930–945 | ............ |
| Acmite, Eker | ............ | 925–930 | ............ |
| Hornblende | ............ | ............ | 1187–1200 |
| Pargasite, Pargas, 1.53 $Fe_2O_3$, 1.32 FeO | ............ | 1140–1155 | ............ |
| Hornblende, Czernosin, 5.81 $Fe_2O_3$, 7.18 FeO | ............ | 1075–1080 | ............ |
| Vesuvius, 2.86 $Fe_2O_3$, 19.02 FeO | ............ | 1085 | ............ |
| Barkevikite, Langesund | ............ | 1070 | ............ |
| Riebeckite, St. Peter's Dome | ............ | 940 | ............ |
| Ænigmatite, Kangerdluarsuk | ............ | 935 | ............ |
| Arfvedsonite, Narjakasik | ............ | 920 | ............ |
| Chromite, Kraubath | ............ | >1450 | ............ |
| Pleonast, Monzoni | ............ | 1270 | ............ |
| Orange City | ............ | 1250–1260 | ............ |
| Magnetite, Mulatto | ............ | 1195 | 1250–1450 |
| Fluorite | 1387 | ............ | ............ |
| Hematite, Waldenstein | ............ | 1360 | ............ |
| Titanite | ............ | 1200 | ............ |
| Apatite, Renfrew | ............ | 1270 | 1225 |

For comparison it is interesting to note the following melting points of some of the metals:

| | | |
|---|---|---|
| Platinum | 1753°. | Waidner and Burgess. |
| Nickel | 1435–1440°. | Day and Sosman. |
| Gold | 1059.3°. | Day and Clement. |
| Copper | 1081.0°. | Day and Clement. |
| Silver | 958.3°. | Day and Clement. |
| Zinc | 418.5°. | Day and Clement. |
| Cadmium | 321.7°. | Day and Allen. |

[1] Day, A. L., Allen, E. T., and others. Am. Jour. Sci., 4th Ser., vol. 19, 1905, p. 93; vol. 21, 1906, p. 100; vol. 22, 1906, p 265, and p. 385; and in publications of the Carnegie Institution.

[2] Doelter, C. Beziehungen zwischen Schmelzpunkt und chemischer Zusammensetzung der Mineralien. Tscher. min. petr. Mitth., vol. 22, 1903, pp. 297–321.

[3] Joly, J. Proc. Royal Irish Acad., Ser. III., vol. 2, 1891, and Congr. géol. intern., VIII, Paris, 1900.
Cusack, R. *Ibid*, vol. 4, 1896.

**Polymorphism.** — Some substances are known to occur in more than one kind of crystalline form, that is, with different crystallographic molecular arrangements. For example, monoclinic and orthorhombic sulphur; the different forms of $TiO_2$, rutile, anatase, brookite. Compounds occurring in such a manner are said to be POLYMORPHIC.

They yield identical liquids, solutions and vapors, and must have identical chemical molecules. Whether there is any other molecular difference between polymorphic forms of one compound than the crystallographic arrangement of the molecules is not always determinable. In some cases the change from one polymorphic phase to another may be accompanied by molecular polymerization. In general, polymerization, or the existence of different multiples of the simplest molecules in different phases of a substance, is indicated upon the transition, or inversion, of a substance from one phase to another by the liberation, or absorption, of a large amount of heat. Whether there is polymerization in the pyrogenetic compounds upon crystallization from molten liquids is a debated question. According to Doelter[1] some of the pyrogenetic silicate minerals yield much heat upon crystallization, indicating polymerization upon crystallization. But Vogt[2] concludes from his study of slags that there is little or no polymerization of the silicates formed in them.

**Enantiotropism and Monotropism.** — The change from one polymorphic crystal form of a substance to another in some instances takes place with great slowness upon change of conditions; in other cases rapidly. In some cases the transition may take place in either direction upon change of conditions; the process is then ENANTIOTROPIC. In other cases the transition is only possible in one direction, — from a metastable to a stable condition. Such a process is MONOTROPIC.

Quartz and tridymite are enantiomorphic forms of silica, $SiO_2$. A transition point between them occurs at about 800° C. Above this temperature tridymite is the stable form; below 800° quartz is stable. But on account of the high internal molecu-

[1] Doelter, C. Physikalisch-chemische Mineralogie, Leipzig, 1905, p. 101.

[2] Vogt, J. H. L. Die Silikatschmetzlösungen, II, p. 147. Christiania. 1904.

lar friction within both of these forms at temperatures near the inversion point, 800°, a transition from one to the other cannot be effected readily. Tridymite cannot be transformed to quartz in the laboratory without the aid of a catalyzer, such as a mixture of potassium chloride and lithium chloride. Tridymite forms from quartz when this is in very small fragments. When in larger crystals, quartz may be heated rapidly to 1600° without passing into tridymite before melting. The liquid silica at this temperature is extremely viscous.[1]

The polymorphic forms of $MgSiO_3$ crystallized in the laboratory[2] present a case of enantiotropism and monotropism. There are five forms of magnesium metasilicate. One, $\alpha$-$MgSiO_3$, is orthorhombic, and in crystal habit, index of refraction and birefringence resembles forsterite, magnesium orthosilicate. It forms very near 1524° and passes by enantiotropic transition at 1365° into the $\beta$-form. It can only be obtained by sudden chilling of the liquid. The second, $\beta$-$MgSiO_3$, is a monoclinic pyroxene formed below 1365°, and stable at all temperatures below this point. The other three forms pass into the second at temperatures between 1150° and 1300°. The third form is orthorhombic, and is identical with enstatite. It may be made by heating the glass of $MgSiO_3$ at a temperature between 1000° and 1100°. It passes into the monoclinic form very slowly upon heating, the transition beginning at temperatures between 1260° and 1290°. In the presence of a solvent it may change at temperatures as low as 800°. The fourth form is monoclinic, corresponding to amphibole in its optical properties. It forms in very small quantities by rapidly cooling liquid $MgSiO_3$. The fifth form is an orthorhombic amphibole, close to the monoclinic amphibole in its properties. It is obtained by heating the molten silicate high above the melting point, and cooling rapidly in air. Both of the amphiboles pass into the monoclinic pyroxene upon heating sufficiently. The cooling of this form does not convert it into any one of the lower forms.

Enantiotropic and monotropic relations are illustrated by the accompanying diagrams, although the actual vapor pressures of

[1] Day, A. L. and Shepherd, E. S. Am. Jour. Sci., vol. 22, 1906, p. 275.

[2] Allen, E. T., Wright, F. E., and Clement, J. K., Am. Jour. Sci., vol. 22, 1906, pp. 385–438.

many crystals are too low to be measured. In Fig. 1, a case of enantiotropism, $t$ is the axis for temperature; $p$, that for vapor pressure; *abc* is the vapor tension curve for the liquid phase; *ed*, the vapor tension of the crystal phase stable below the inversion point $T_2$; *db*, the vapor tension of the crystal phase stable above the inversion point $T_2$; $T_1$ is the melting point of the crystal phase stable at higher temperatures. At $T_2$ the two crystal phases have the same vapor pressure and are therefore in equilibrium with one another. At $T_1$ the crystal form stable at

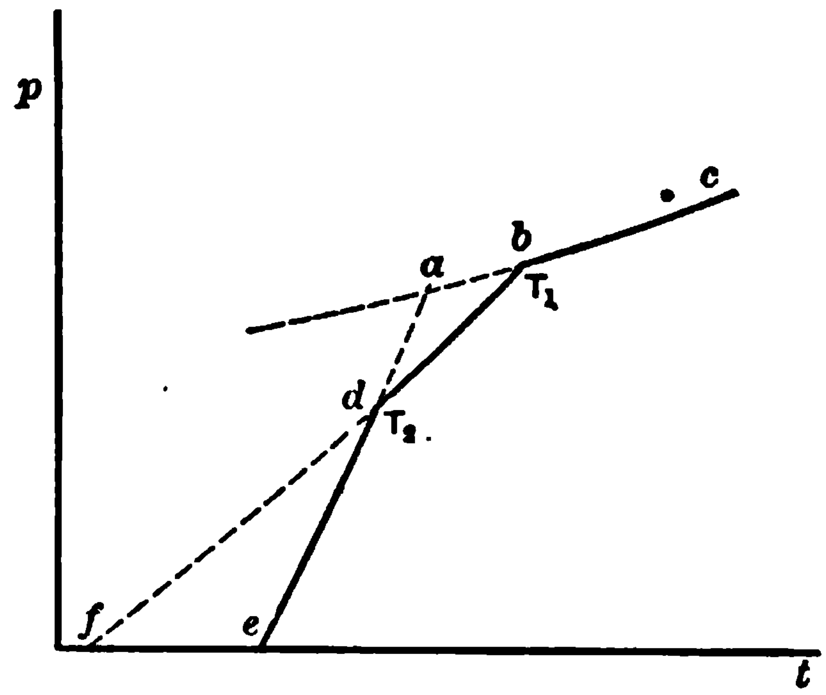



FIG. 1.

higher temperatures has the same vapor pressure as the liquid phase, so the solid and liquid are in equilibrium with one another at this point.

Since a crystal stable at higher temperatures can in many cases be cooled below the inversion point without being converted into a phase stable at lower temperatures, the curve *bd* may be imagined as being extended beyond the point *d*. But in most cases crystals stable at lower temperatures cannot be heated far above an inversion point without changing into another phase. So that the curve *ed* can seldom be extended to intersect the melting curve. That is, it seldom happens that a crystal stable at lower temperatures can be melted before inversion to the other crystal phase takes place. This, however, may be accomplished with quartz, without transforming it to tridymite.

In Fig. 2, a case of monotropism, *abc* is the vapor pressure curve for the liquid; *eb*, that for the stable crystal phase; *da*, that for the unstable crystal phase; $T_1$ is the melting point for the stable phase; $T_2$, that for the unstable phase. At $T_2$ the unstable

form is in equilibrium with the liquid phase, and this is its melting point. The stable phase is in equilibrium with the liquid at $T_1$, which is its melting point. For any given temperature the stable form has the lower vapor pressure. The unstable form always has the lower melting point, but it frequently passes into the stable form before melting. If the two curves *eb* and *da* were

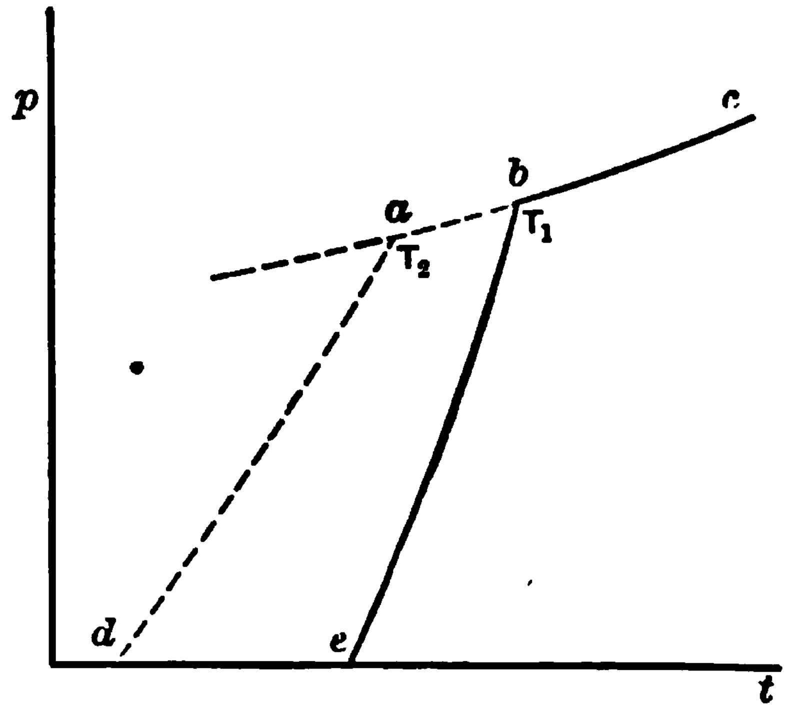



FIG. 2.

extended their intersection would lie above *abc*, that is, above the melting point of each crystal phase. These phases, therefore, cannot exist in equilibrium with each other.[1]

**False Equilibria.** — When the transition from one polymorphic form to another takes place with great slowness, the two forms may exist in contact with one another for long periods of time. In such cases there is no real equilibrium between the forms. The condition is one of apparent, or FALSE EQUILIBRIUM. There are numerous instances of false equilibria in igneous rocks, such as the association, and contact, of quartz and tridymite; of glass and crystals of the compounds composing it; intergrowths of monoclinic and orthorhombic pyroxenes; and intergrowths of amphiboles and pyroxenes. In fact, nearly all rocks are systems of false equilibria. The relative stability of various crystal compounds in igneous rocks has an important bearing on their resistance to decomposing or metamorphosing agencies. For a discussion of the conditions affecting the production of polymorphic forms see Chapter V.

[1] Roozeboom, Heterogenen Gleichgewichte, Braunschweig, 1901, Part 1, p. 158, also Allen, Wright and Clement, Am. Jour. Sci., vol. 22, 1906, p. 411.

## SOLUTIONS

Since the magma from which an igneous rock has solidified was in a liquid state at high temperature, and its composition was not simple, the molten magma must have been a solution from which minerals crystallized to form the rock. It is necessary then to consider the properties of liquid solutions, both with respect to their physical characters and possible molecular constitution; and the probable chemical character and the reactions that may take place in them; and also the processes of solidification that may convert them into amorphous, rigid solutions, or glasses, or into crystallized minerals.

### PHYSICAL CHARACTERS OF SOLUTIONS

Defining a solution as a homogeneous mixture which cannot be separated into its constituent parts by mechanical means,[1] there may be solutions of gases, liquids, or solids in one another in various ways. While gases may mix with gases to any extent, provided they do not combine chemically, the mixture or solution of liquids in liquids, or of solids in liquids, takes place to quite different degrees in different cases and under different conditions. The solution of solids by solids takes place with great difficulty, but is known to happen in certain instances.

**Solution of Gases in Liquids.** — Every liquid may dissolve every gas to a greater or less extent, depending upon the nature of both substances. In one set of cases the solution may take place without chemical action, and all the gas may be removed from the liquid by lowering the pressure or raising the temperature. In another set of cases some of the gas may combine with the liquid and not be recoverable.

In the first instance " the quantity of a gas dissolved by a specified quantity of a liquid is proportional to the pressure of the gas." The volume of a gas being inversely as the pressure, a specified quantity of a liquid dissolves the same volume of a gas at all pressures. This is Henry's Law. When a mixture of gases is dissolved by a liquid each constituent gas is dissolved as though the other gases were not present; that is, it is absorbed under a pressure corresponding to its quantity in the mixture.

[1] Ostwald, W. Solutions, translated by M. M. Pattison Muir, 1891, p. 1.

The amount of gas absorbed by different liquids varies with the character of the gas and of the liquid, and must be determined for each case.

When a liquid absorbs gas its volume increases, usually in proportion to the volume of the gas dissolved, but the increase is slight compared with the volume of the gas, which is often greatly condensed. Thus 1 volume of water at 0° C. and at atmospheric pressure dissolves 1049 volumes of ammonia gas, and becomes 1.487 volumes of ammonia-solution.[1] But with a gas that is only slightly soluble in water, as carbon dioxide, the increase in volume for a condition of saturation is very small. In this case the increase is only .0021 of the total volume for 2° C.

The amount of gas absorbed by a liquid decreases with increase of temperature for any given pressure. At some particular temperature it may be entirely driven out of the liquid.

When the absorbing liquid is a solution of salts, there is apt to be chemical action upon the accession of a gas, in which case the laws just stated are modified according to the amount of chemical action.

When gas is dissolved in a liquid, its particles become as much a part of the liquid or solution as those of any other of its constituents. They diffuse through it in the same manner as other components. The possible state of aggregation of the gas particles will be discussed in connection with that of other substances in solution in a subsequent paragraph.

**Solution of Liquids in Liquids.** — The ability of liquids to dissolve in one another, or to form homogeneous mixtures, varies greatly with their nature. Some mix together in all proportions at all temperatures and pressures like gases, others dissolve in one another partially, that is, within certain proportions, which vary with temperature; in some cases being wholly miscible at some temperatures and only partially so at others. There are a few liquids known which do not appreciably dissolve certain other liquids. Such liquids must show no measurable vapor-pressure at the temperature of experimentation, for if the vapor or gas of one liquid were in contact with another liquid it would be absorbed to some extent.

When liquids dissolve in one another in all proportions the properties of the mixture is not the sum of the properties of the

[1] Daniell, A., Text Book of the Principles of Physics, New York, 1895, p. 329.

constituent liquids. There is a change in volume, usually a diminution, but in some instances an increase. There is also a change of temperature; in some cases an evolution of heat, in others an absorption of it. But there is no fixed relation between the volume and thermal changes. In some cases heat is evolved upon the contraction of the volume, in others upon an expansion. In many cases, however, the properties of the mixture are not very different from the sum of those of the component liquids.

Most liquids do not dissolve one another in all proportions, but only within definite limits for certain temperatures. If one liquid dissolves another only partially, then the second will also dissolve the first partially. In general, liquids which are only partially miscible at low temperatures become completely miscible at higher temperatures. Conversely, mixtures of some liquids that are homogeneous at high temperatures may separate into unlike portions when the temperature is reduced. Each portion of the heterogeneous liquid will consist of a larger proportion of one kind of liquid with smaller amounts of the other component liquid, or liquids.

**Solution of Solids in Liquids.** — When a solid is brought into contact with a liquid, solution of the solid takes place to a greater or less extent, depending on a number of factors; first, on the nature of the solid and on that of the liquid, some solids being readily soluble in certain liquids, others almost not at all, though the most delicate tests may detect very minute traces of the solids, as of platinum in water. The ability of a liquid to dissolve a solid also varies with temperature, generally increasing with rise of temperature, but in some cases decreasing with increase of temperature.

As in the previous cases, already discussed, it is necessary to distinguish those cases of solution of solid in liquid in which there is chemical action between the two, from those in which there is no chemical action. The statements that follow refer to those cases in which no chemical action takes place, but they apply in certain particulars to those in which there is chemical action.

**Saturation and Supersaturation.** — There is always a limit to the amount of a solid which can be dissolved by a given volume of any liquid at a given temperature and pressure. This varies

with the kind of solid and liquid. When this maximum amount is reached, the liquid is said to be SATURATED. In some cases, however, the liquid may be made to carry in solution more than the amount it is capable of dissolving from the solid. In such a condition it is said to be SUPERSATURATED. Supersaturation may be attained in some instances by lowering the temperature of the solution below that at which it is saturated by a given compound, when under favorable conditions it may retain in solution more of the solid than it is capable of dissolving at that temperature. The ability of a compound to supersaturate a solution and the extent to which it may exceed the amount required for saturation, varies greatly with different pairs of solids and liquids. In general, it has been found that substances that resemble one another chemically have the greater tendency to form supersaturated solutions. Thus supersaturated hydrous solutions are formed most readily by salts crystallizing with "water of crystallization."

As to the possible molecular process of solution of solid in liquid, there is a close analogy between it and that of the melting of a solid, and also between it and the act of vaporization. It is supposed that particles, or molecules, tending to leave the solid to a greater or less extent, as when vaporization takes place from a solid, are held to the solid by the attraction of its molecules, and that this molecular cohesive action is overcome by the attraction of the molecules of the liquid in contact with the solid, so that they escape more readily into the liquid than into gas. Those particles of the solid entering the liquid move about in it, gradually diffusing through it. Along the surface between solid and liquid, they move toward the solid as well as away from it. So long as more leave the solid than return to it, there is solution of the solid in the liquid. When the numbers leaving and returning to the solid are the same, there is equilibrium, and solution ceases. This is attained under definite conditions of temperature and pressure when the concentration of the substance in the liquid has reached a certain value, and does not depend on the relative quantities of the solid and liquid. It is in this respect analogous to vapor-pressure over a liquid, and the concentration of a substance in solution has been called SOLUTION-PRESSURE.[1]

[1] Nernst, W. Zeitschr, für phys. Chemie, 4, 1889, p. 150.

When a solution is not in contact with a solid mass of the substance in solution, the concentration may be increased beyond the point at which equilibrium with the solid takes place, without the separation of the substance from the solution, and in general at the point of saturation it requires the presence of the substance in a solid form to induce separation. But it may be present in microscopic or even submicroscopic form without being noticed by the unaided eye, and it often requires great caution to exclude particles which may act as nuclei of crystallization from saturated solutions that are being tested in the laboratory.

Crystals isomorphous with the dissolved substance behave toward a saturated solution as crystals of the substance in solution, and prevent supersaturation by acting as nuclei on which the solid may separate out.

Compounds that readily form supersaturated solutions commonly crystallize in large well-formed crystals, but when separation of solid takes place upon slight supersaturation there are numerous small crystals, for there is not time for the first crystals to grow before diffusion produces a supersaturated solution near them.[1]

Supersaturation of a solution may be effected by gradual lowering of temperature in a quiet liquid, free from solid particles of the substance in solution. It may be prevented by the presence of such solid bodies or of isomorphous substances; by agitation of the liquid during cooling; and in laboratory experiments by the scratching of the inside of the vessel containing the liquid.

**Influence of Temperature on Solubility.** — In most cases an increase of temperature increases the amount of substance that can be taken into solution in a given volume of a liquid. But in some cases the reverse is true. More exactly it may be stated that when heat disappears in the solution of a substance, is absorbed, then solubility increases with rising temperature; but when heat is produced upon solution solubility decreases as temperature increases. In general, solubility increases with increasing temperature more rapidly than the temperature increases, but no definite mathematical expression for the rate of increase has as yet been discovered.

When a solid is dissolved in a liquid and this is heated above the critical point under sufficient pressure the solid remains in solution in the gas. From this it is evident that the kinetic energy in such a solution must be very great, and the molecular mobility very much higher than when the solution is in liquid phase; permitting much more rapid molecular diffusion and interaction.

When solution takes place at the melting point of a solid there is no sudden increase in the solubility of the substance, but there is a marked change in the rate of solubility with change of temperature.

[1] Ostwald-Muir. Solutions, p. 60.

**Volumetric Changes Upon Solution.** — In most cases studied—aqueous solutions —solution of solid in liquid is accompanied by contraction of volume; that is, the volume of the solution is smaller than the sum of the liquid and solid at the same temperature. The amount of contraction depends upon the proportion between solvent and solid, being greater as the proportion of the solvent is greater.

**Influence of Pressure on Solubility.** — If the solution of a solid in a liquid is accompanied by contraction, the general case for aqueous solutions, then solubility is promoted by increase of pressure for a given temperature. When solution takes place with expansion of volume, solubility is retarded by increase of pressure.

**Relation Between the Composition of Solid and Solution and Solubility.** — While no definite relation has been discovered between the characters of the solid and of the liquid and the solubility of the solid, it may be said, that solubility is determined to some extent by the chemical analogies of the substance to be dissolved and the solvent. Those that are somewhat related chemically generally dissolve in one another more readily than those that are quite distinct chemically. But no regular relationships have been discovered for the solubility of groups or series of analogous compounds when these become dissociated upon solution, as is the case with many salts in aqueous solution. On the other hand, when compounds enter solution without dissociation or ionization, definite relationships between the characters of the compounds and their solubility in one another have been found to exist. Thus the most fusible of a group of isomeric organic (hydrocarbon) compounds is also the most soluble, independently of the nature of the solution.[1]

**Common Solubility of Several Substances in one Liquid.** — When two solids in solution do not react on each other chemically, the solution may become saturated with respect to each, and the proportion between solid and solution does not affect the equilibrium of saturation. But the amount of each necessary to saturate the solution at the same time is not exactly the same as when one is dissolved alone; and is somewhat smaller.

[1] Ostwald-Muir. Solutions, p. 81.

When the two substances in solution are capable of forming a double salt upon crystallization several cases are possible. (1) No double salt may have formed; the case is like that just described. (2) When the double salt (mA+nB) has been formed then either the salt A, or the other salt B, may be present in excess of the amount necessary to combine with the other salt to form the double salt; two states of equilibrium may result: one in which the double salt is in equilibrium with A, and the other in which it is in equilibrium with B. On adding one salt, B, to the saturated solution of the other salt, A, as the double salt is formed, A is taken out of solution; the concentration with respect to A is decreased, and when an excess of B is added, all of A will be withdrawn from the solution in the form of the double salt. The solution contains B and the double salt (mA + nB). Eventually it may become saturated with respect to B and the double salt.

When the two salts are isomorphous and are capable of crystallizing together in all proportions the composition of the saturated solution changes continuously with the composition of the isomorphous mixture; by adding successive quantities of B it is possible to displace A entirely from the solution, that is, so far as its presence may be determined by ordinary methods.

**Solution of Solid in Mixtures of Liquids.** — When two liquids dissolve together into a homogeneous liquid the solubility of a solid in the mixture depends upon its solubility in each liquid separately, but no definite laws controlling the degree of solubility are known. As a result of this behavior a solid may be separated from a saturated solution by adding another liquid in which the substance is less soluble than in the first.

**Vapor-pressure of solutions** varies with the concentration, being higher for the pure liquid than for the solution, and decreasing proportionally to the concentration until saturation is reached. But when the solution at this point is rather concentrated the proportionality of the change is not strictly maintained. More exactly, for solutions of medium concentration the relative lowering of vapor-pressure is proportional to the concentration. In general it may be said that "the lowerings of vapor-pressures of solutions in different solvents are equal when the proportion of the number of molecules of the dissolved substance to the number of molecules of the solvent is the same." This is true for solutions of medium concentration. A still more general law is that "the relative lowering of vapor-pressure is proportional to the ratio of the number of molecules of the dissolved substance to the total number of molecules in the solution."[1]

[1] Ostwald-Muir, Solutions, pp. 170 and 171.

Changes in the vapor-pressure of solutions have been used to determine the molecular weights of some substances in solution, or, when these are well established by other means, to determine the molecular condition of substances in solution. The study of the vapor-pressure of solutions of metals in mercury (amalgams) by W. Ramsay[1] has led to interesting conclusions in some cases. In all cases the vapor-pressure of mercury was lowered. There appears to be a tendency of the metals to form the simplest molecules possible, that is, molecules consisting of single atoms. In several cases (potassium, calcium, barium) the results were abnormal, indicating something less than atoms. Most of the other metals appeared to have been reduced to atoms. But aluminium and antimony show a tendency to form complex molecules. The behavior of the metals in solution in mercury agrees with their behavior in the gaseous state.

**Freezing points of solutions** are in general lower than those of the component substances, solute or solvent. The amount of lowering of the freezing point of a liquid brought about by the substance dissolved in it is approximately proportional to the concentration. More exactly, if one molecule of any substance is dissolved in one hundred molecules of any liquid of a different nature, the lowering of the freezing point of this liquid is always nearly the same, and approximately 0°.63; Raoult's law.[2] This is applicable to many solutions, but there are certain kinds of solutions, chiefly aqueous solutions of acids, salts, and bases, in which there is a notable deviation from this law, indicating by the greater depression of the freezing point that there must be some dissociation of the substances in solution.

In the special cases of metals dissolved in mercury, or in liquid sodium or tin (amalgams), the law has been found equally applicable. The metals appear to exist in their atomic state, and one atom of a metal dissolved in one hundred atoms of the solvent produces a constant lowering of the freezing point, almost regardless of the nature of the dissolved metal. In the case of a few metals, especially aluminium, the atomic lowering of the freezing point is much smaller, indicating more complex molecules.

A study of the melting point of two substances in solution in one another has shown that for a particular mixture of the two there is a minimum freezing point at which each saturates the other and both may solidify at the same time. Such a mixture is called a EUTECTIC, and the freezing point is known as the

[1] Chem. Soc. Jour. Trans. 1889, p. 521.

[2] Jones, H. C. The Elements of Physical Chemistry, 1903, p. 207.

EUTECTIC POINT. Solutions of a salt in water in such eutectic proportions were investigated by Guthrie and called by him CRYOHYDRATES.

When two solids that are capable of forming a solution in one another at ordinary temperatures are brought in contact with one another, they pass into solution along the surface of contact and eventually become a liquid solution; the most familiar example is ice and common salt. Potassium and sodium behave in a precisely similar manner at ordinary temperatures.

Since substances in any state dissolve in one another, it is better to consider the action as mutual and to think of each as the solvent for the other than to speak of either as the solvent or the dissolved substance. The common practice is to speak of that one which remains liquid longest upon the gradual solidification of the solution as the solvent of those substances that solidify from it. But, since in nearly all kinds of liquid solutions a eutectic mixture is possible, from which both substances solidify simultaneously, the terms solvent and solute lose their significance. A fuller discussion of this subject will be found in Chapter V, in connection with the separation of substances from solutions.

**Solid Solutions.** — The existence of homogeneous solids whose composition is not that of a single, or definite compound, but represents a mixture of several compounds or substances, is becoming more and more generally recognized. Upon investigation they exhibit many of the characteristics of liquid solutions, and are in fact solid solutions. An example of solid solution is lime-soda-feldspar. Rock glass, which consists of the same mixture of compounds as the liquid magma, and, from what has already been said concerning various states of matter, is merely a highly viscous liquid, or amorphous solid, and may be called a *rigid solution*, in distinction to the technical term, solid solution. The subject of solid solutions will be treated systematically as follows.

**Solution of Gases in Solids.** — Gases are absorbed by solids in such a manner in some cases as to be true solutions, as when hydrogen is absorbed by palladium hydride, in which case the amount of gas dissolved, or absorbed, is proportional to the pressure.

When a gas is readily soluble in a solid it may traverse the

solid freely. Thus hydrogen passes through white hot palladium, or platinum, carbon dioxide passes through glowing iron. The solubility of gases in solids varies greatly with the kinds of substance.

Gases may also be condensed upon the surface of a solid, especially on the surface of cavities in a finely porous solid, such as animal charcoal, or platinum-black. The action is then similar to capillary action of liquids. The amount of gas which may be adsorbed in this way in certain cases is so great that the condensation is equal to that of liquefaction of these gases. But this is not the same as solution of gas in compact solids.[1]

**Solution of Liquids in Solids.** — Investigation of the behavior of the water contained in some crystals when they are highly heated shows that it must be present as matter in solution in the solid, and, presumably, at ordinary temperatures as liquid in solution in solid. The work of Friedel[2] and also of Tammann[3] upon zeolites, and of Allen and Clement[4] on tremolite, kupfferite, beryl, and some other minerals, has shown that water is given off by these minerals at high temperatures in a gradual manner, without destroying the homogeneity of the crystals, and with only slight modification of their optical properties. In some instances water vapor may be again absorbed or dissolved by the crystals upon cooling. In the case of the zeolites Friedel found that they maintain true equilibria with water vapor at low pressures. This does not appear to be the case, however, with tremolite and diopside studied by Allen and Clement, which may present false equilibria. The absorption of liquids by capillary attraction in the cavities of porous solids is not to be confused with true solution.

**Solution of Solids in Solids.** — There are several ways in which the existence of *solid solutions* and the diffusion of material in the solid state have been established. The most striking

[1] The subject of the presence of gases in rocks and the possibility of their being in part in solution in the rock minerals is treated at considerable length by R. T. Chamberlin in a recent publication of the Carnegie Institution, Publication No. 106, The Gases in Rocks, Washington, 1908.

[2] Bull. Soc. Min., vol. 19, 1896, and vol. 22, 1899.

[3] Zeitschr. Phys. Chem., vol. 27, 1898.

[4] Am. Jour. Sci., vol. 26, 1908, pp. 101–118.

example of diffusion of solids within one another is the experiment by Roberts-Austen[1] in which disks of gold and cylinders of lead, properly smoothed and cleaned, were clamped together and allowed to remain standing for four years at a nearly constant temperature of 18° C. At the end of this time the two metals were found adhering to one another, and tests of the lead showed that gold had penetrated about eight millimeters into the lead, the greatest concentration of the gold being nearest the gold disk. Zinc objects covered with a thin layer of copper become white in time by the gradual increase of zinc in the copper. It is known that in crystals of alums made up of different layers there is a blending of the layers in time. Examples of chemical interaction between solids are known. A SOLID SOLUTION may be defined as a "*solid, homogeneous complex* (crystal), *in which the properties can change without destroying the homogeneity.*"[2] There are close analogies between the properties of solid solutions and those of liquid solutions.

The investigations of Day[3] and his colleagues in the Geophysical Laboratory of the Carnegie Institution in Washington upon silicates of calcium and magnesium in mixtures of various proportions have demonstrated the ability of crystals of calcium metasilicate, $CaSiO_3$, magnesium metasilicate, $MgSiO_3$, and of calcium-magnesium metasilicate, $CaMg(SiO_3)_2$, to take up in homogeneous mixture, that is, in solid solution, variable amounts of each other and of other constituents of the solution from which they crystallize.

Thus it was found that the metasilicate of calcium is able to take up in solid solution a small amount of either CaO or $SiO_2$, according to which preponderates in the lime-silica solution. In the series of solutions containing various proportions of $CaSiO_3$ and $MgSiO_3$ six different solid solutions appear, in four of which the lesser component is not more than three or four per cent of the principal one. In two cases, however, the proportions are much greater. Thus wollastonite ($\beta$-$CaSiO_3$) may take on various amounts of diopside to a maximum of 17 per cent of diopside to 83 of wollastonite, or about twenty per cent of the wollastonite by weight. At this point the solid solution becomes saturated, for with more diopside the wollastonite crystals cease to be transparent and homogeneous. Pseudowollastonite

[1] Proc. Roy. Soc., 67, 1900, p. 101.

[2] Jones, H. C. The Elements of Physical Chemistry, 1903, p. 268.

[3] Am. Jour. Sci., vol. 22, 1906, pp. 265–302 and pp. 385–438, *ibid*, vol. 28, 1909, pp. 1–47.

($\alpha$-$CaSiO_3$) can dissolve only about four per cent of diopside. Diopside can dissolve as much as 60 per cent of its own weight of $MgSiO_3$, the mixed crystal containing about 66.5 $MgSiO_3$, 33.5 $CaSiO_3$. The saturated solution (mixed crystal) is very similar in its properties to pure diopside, but all the physical properties change continuously with addition of $MgSiO_3$. Diopside can dissolve only about 5 per cent of its own weight of $CaSiO_3$. The behavior of the physical characters of the crystals and solutions shows that the compound $CaMg(SiO_3)_2$, diopside, is a definite one, and that variations from it in the composition of crystals are to be considered as solid solutions or mixed crystals.

These investigators conclude that there is a tendency of crystallizing substances to absorb during the process of crystallization large or small amounts of other materials. The more closely similar the absorbed material is to the absorbing crystal in molecular arrangement, molecular spacing, and other physical characters the greater the amount, in general, which can be taken up. When two substances are so much alike physically that their solid phases, crystals, are miscible in one another in all proportions they are said to be ISOMORPHOUS, as for example the lime-soda-feldspars.[1]

There are several kinds of solid solutions that may be distinguished from one another. (1) Substances miscible in one another in all proportions; isomorphous substances, such as the lime-soda-feldspars. (2) Substances miscible in one another within certain limits, and having like crystal characters; limited isomorphism, such as diopside and $MgSiO_3$. (3) Substance miscible to some extent, but without crystallographic, or chemical, resemblance, such as diopside and $SiO_2$, or CaO. (4) Solidified solutions, not crystallized solids, rigid solutions, such as rock glasses.

The preceding statements deal with solutions in regard to their kind, their modes of formation, and some of their physical properties. It is necessary to consider the possible condition of the dissolved substance within the solution, or the molecular constitution of the solution.

**Diffusion.** — When gas is admitted to a space not occupied, that is, a vacuum, it expands at once until it fills the whole space. If it is admitted to a space already occupied by another gas the two gases permeate gradually one another until there is

[1] Day and Allen, Isomorphism and Thermal Properties of the Feldspars, Carnegie Institution Publication, Washington, 1905.

a homogeneous mixture of both gases. They diffuse through one another. The lighter gas will travel more rapidly than the heavier. The rate at which diffusion takes place is greater the greater the difference between the pressures exerted by each gas, that is, the greater the condensation of one gas above that of the other. When two or more gases diffuse through the same medium their rates of diffusion are proportional to the mean velocity of the molecules in each gas, that is, they are inversely proportional to the square roots of the density of each.

When gas is dissolved by a liquid it diffuses through the liquid until it is equally distributed. Its behavior is the same as when it diffuses through a gas, except that the rate of diffusion is much less. Similarly when any substance, liquid or solid, is dissolved in a liquid it diffuses through the liquid until it is uniformly distributed and the mixture is homogeneous. There is a movement of the dissolved material from that part of the liquid where it is most abundant, or most concentrated, toward the part where it is less concentrated. The cause of this movement is the same as that producing osmose, and has been called OSMOTIC PRESSURE, or SOLUTION PRESSURE.

With regard to osmotic pressure, it is known to increase with temperature, the law being that it increases in proportion to the absolute temperature of the solution. The close analogy between osmotic pressure and gas pressure is shown by the fact that solutions which at the same temperature exhibit equal osmotic pressures contain equal numbers of molecules of the dissolved substance in equal volumes. This has been expressed by van't Hoff as follows: The osmotic pressure exercised by a substance in solution is identical in value with the gaseous pressure which it would exhibit if the same quantity of it were contained as a gas in the same volume at the same temperature. This applies to dilute solutions of substances that are not ionized.

The rate of diffusion, or the amount diffused in a given time, varies with the kind of substance and the liquid dissolving it, but the general law, announced by Fick, is that for each kind of substance the quantity which diffuses through a given area is proportional to the difference between the concentrations of

the two areas infinitely near one another, or is proportional to the difference in concentration. This law must be modified for solutions of high concentration, for the diffusion rates decrease gradually as concentration increases. Moreover, it does not apply rigidly to those cases in which there are molecular changes in the condition of the dissolved substance upon dilution of the solution — ionization.

With regard to the time required for diffusion, it has been observed that the quantity diffused is proportional to the square root of the time occupied. The distance over which a determinate concentration extends is also proportional to the square root of the time of diffusion. As to the effect of temperature on diffusion, it has been found that the quantities diffusing in equal times increase very nearly in proportion to the temperature. It has also been found that there is a somewhat regular arrangement of molecular diffusion-values; that is, the number of molecules of different substances diffusing under equal conditions. Chemically similar compounds of elements closely related and belonging to the same group, such as the haloids of potassium and of sodium, or the sulphates of the magnesium group, have approximately equal values. The bearing of this on the possible differentiation of magmas will appear later, in Chapter VII. A close parallelism is noticeable between the rates of diffusion and the electrical conductivities of substances.[1]

When several substances diffuse from a mixture each substance diffuses almost independently of others, each nearly at its own specific rate. This fact has been employed by Graham to separate mixed substances. In one case from a mixture of equal amounts of two salts a solution was obtained by diffusion in which the salts were in the proportion of 90.6 : 9.4. No definite relationship between the relative diffusivities of substances diffusing from a mixture and the specific diffusivity of each substance when diffusing alone has been discovered. It appears that the difference between their diffusivities when alone is somewhat increased when they diffuse simultaneously.

When the rates of diffusion of various salts are compared with one another, as has been done by Marignac, it is found that the rates of diffusion

[1] Ostwald-Muir, Solutions, pp. 135, 136, and 139.

of the acids are related to those of the metals so that all the salts of any specified acid always follow in the same order, according to the bases, whatever the acid may be; and so also, all the salts of any metal follow in the same order, according to the kinds of acids, independently of the nature of the metal. The order of diffusion-coefficients is indicated by the following table, in which those with the highest diffusivity stand at the top.

| | |
|---|---|
| Cl, Br, I | H |
| $NO_3$ | K, $NH_4$ |
| $ClO_3$, $ClO_4$, $MnO_4$ | Ag |
| F | Na |
| $CrO_4$ | Ca, Sr, Ba, Pb, Hg |
| $SO_4$ | Mn, Mg, Zn |
| $CO_3$ | Cu |
| | Al |

There is a great similarity between the order of diffusivities as represented above and the electrical conductivities of salt solutions.[1]

**Homogeneity of Solutions.** — A solution all of whose portions exist under equal temperatures and pressures should in time become homogeneous through the diffusion of whatever may be in solution in it. Without convection currents or other movements of the liquid mass the time required theoretically for a heterogeneous liquid to become homogeneous is infinite. But currents within the liquid tend to promote complete diffusion. On the other hand, a homogeneous, or nearly homogeneous, liquid all of whose portions are not under equal temperatures or pressures will not remain homogeneous, but through diffusion of its constituents will alter its concentration in different portions until the osmotic pressure corresponds to that required by the different temperatures and pressures.

The requirements of changes of pressure, whereby greater density, concentration, of solution should appear in portions of the liquid under greater pressure, have been investigated theoretically by means of the principles of thermodynamics by Gouy and Chaperon,[2] who found that the increase in those cases where a small change of concentration produces change of density would be very small even in a depth of 100 meters, and would take place with extreme slowness.

When, however, there is a difference of temperature in different parts of the solution, there is a corresponding change in

[1] Ostwald-Muir, Solutions, p. 144.
[2] Ann. chim. phys. (6) 12, 1887, p. 384.

the concentration of the solution so that the solution becomes more concentrated in the cooler portion. This action, sometimes known as *Soret's principle*,[1] was first discovered by C. Ludwig.[2] And, as pointed out by van't Hoff, since the osmotic pressure increases in proportion to the absolute temperature, diffusion must occur from the warmer to the cooler parts until the osmotic pressure has become the same in both, and therefore concentration must vary inversely as the absolute temperature. In more concentrated solutions the ratio between concentration and absolute temperature is somewhat modified.

**Molecular Constitution of Solutions.** — As there may be gaseous, liquid, or solid solutions, it is necessary to consider the possible molecular constitution of matter in each of these states. Conceptions of the constitution of gases are derived from Avogadro's law, that all gases consist within equal volumes at like temperatures, and pressures, of equal numbers of molecules; and also from a study of the changes in volume resulting from the combination of various elements and compounds in a gaseous state. Further information is gained by the liberation of energy, usually in the form of heat, which takes place upon a change in the state of aggregation either within the gaseous state or upon passing from a gas to a liquid, or from a liquid to a solid, or from one form of solid aggregation to another. From these sources of information it is concluded that gases consist of molecules moving independently of each other, and that the molecules are quite differently constituted according to the kind of element or compound, and in some cases according to the temperature of the gas.

The molecules of certain elements in the gaseous state consist of one atom each. This is true of mercury, cadmium, zinc, potassium, sodium, and bismuth; and of iodine at 1700°. The gas molecules of other elements and compounds consist of two atoms each; for example, hydrogen, 2H; hydrochloric acid, H + Cl. A molecule of water vapor contains three atoms, 2H + O, and more complex compounds that may exist as gases are composed of much higher numbers of atoms.

Phosphorus vapor at 1600° consists of diatomic molecules; at lower temperatures the gas molecule contains four atoms. Sulphur vapor at 800° is diatomic; at 500° it consists of $S_8$, $S_6$, $S_4$ and $S_2$. This is known as *association* or *polymerization*.

[1] Ann. chim. phys. (5) 22, 1881, p. 293.
[2] Wien. Akad. Ber. 20, 1856, p. 539.

In a mixture of gases the molecules of each kind of gas must be independent of one another when there is no chemical reaction between them, and we may imagine them as moving about freely among one another, maintaining a uniform distribution.

Upon the transition of sulphur from gas to liquid there is a notable evolution of heat indicating a molecular condensation, so that the liquid molecule of sulphur must contain more than eight atoms. The molecule of water is considered by some to contain twelve atoms $(H_2O)_4$; by others, 9 or 6 atoms, $(H_2O)_3$ or $(H_2O)_2$.

The conception of the molecular constitution of a liquid is derived largely from that of a gas. The molecules move with more or less freedom among themselves, as indicated by diffusion, but cohesive action is relatively greater than in gas, and the mass or weight of the molecules is much greater. The constitution of the molecules composing the liquid is the chief matter for our consideration. As already stated, in certain liquids, such as mercury, the molecules appear to consist of single atoms, and the same is true of certain metals when dissolved in it. But aluminium in the same liquid is probably more complex.

Aqueous solutions present much more varied molecular characters, depending on the nature of the substances in solution. For certain kinds of substances the relations between osmotic pressure, vapor pressure, freezing point and concentration are so uniform that it appears that the substances in solution consist of molecules corresponding in composition, that is, in atomic proportions, to those of the substances or compounds before solution. This is said to be the normal behavior, since it is that of most solids and liquids investigated.

**Ionization.** — When acids, bases, and salts are dissolved in water, the effect on the osmotic pressure, vapor pressure and freezing point is not normal, but of such a kind as to indicate that some of the molecules of these substances in solution have been dissociated. The relative number of molecules of the dissolved substance that are dissociated is greater the more dilute the solution, but there are more dissociated molecules in the more concentrated solution up to a certain degree of concentration.

It has been found that in aqueous solutions the molecules of each kind of compound, acids, bases, or salts, always split up in the same manner. A salt dissociates into the metal element and the

acid radical; for example, $Cu(NO_3)_2$ separates into Cu and $2NO_3$. An acid separates into hydrogen and the acid radical; $H_2SO_4$ becomes 2H and $SO_4$. A base dissociates into the metal element and hydroxyl; KOH becomes K and OH. It appears that water and some other solvents have the power of breaking up the molecules of these compounds, acids, bases, and salts, and of holding the fragments apart from one another and hindering their union.[1] An aqueous solution of such compounds contains, besides undivided molecules of the solute, at least two other kinds of material, which result from the breaking up of the molecules. These subdivisions of the original molecules have distinct physical and chemical properties of their own; they constitute a new set of materials. The hydrogen radical of acids, although a form of uncombined hydrogen, differs totally from the gas which is composed of the same material. It exists as a separate substance only in solution. Compounds like the acid radicals, $NO_3$ and $SO_4$, are not known at all except in solutions. Such dissociated parts of molecules in solution are called IONS, and the process of dissociating molecules to form them is IONIZATION. The substances which are capable of IONIZATION have been called IONOGENS by Smith. They are frequently called electrolytes. Ions are molecules, since they are discrete particles of elements or compounds like other molecules. When a substance dissolves, it does so in molecules similar in form to those of the undissolved substance, and subsequently ions are generated from some of these molecules.

One of the distinctive physical characteristics of ions is that they carry charges of electricity, the metal ions being positively charged, the acidic radicals or ions negatively charged. The amounts of electricity carried by different ions in any given instance are proportional to the valence of each. Thus univalent ions possess like quantities of electricity, bivalent ions twice as much, and so on. In the case of elements having more than one valence the electrical charge of its ions may change; thus, $Fe^{\cdot\cdot\cdot}$ may become $Fe^{\cdot\cdot}$. This may also happen with some compound ions. When the electrical charge is removed from an ion, its properties alter entirely. The oppositely charged ions, resulting

[1] Smith, Alexander. Introduction to General Inorganic Chemistry, 1906, pp. 295 and 296.

from the dissociation of the molecule of an ionogen, are prevented from separating from one another by diffusion by the attractions of the electrical charges. The ions charged with positive electricity (metals) are called CATIONS; those charged with negative electricity (acid radicals and non-metals) are called ANIONS.

**Electrical Conductivity of Solutions.**— The ease with which solutions having like numbers of molecules of different substances conduct electricity under like conditions, depends jointly on the degree of ionization, on the speed with which the ions move, and on the valence of the ions. The most highly dissociated acids, yielding large numbers of speedy hydrogen ions, are the best conductors. Highly ionized bases, such as potassium and sodium hydroxide, come next. The salts are considerably poorer conductors, for, even in cases where they are highly ionized, their ions all move more slowly than hydrogen ions or hydroxyl ions.[1] Concentrated solutions all conduct badly, relatively to the number of molecules entering into them, because only that portion of the substance which is ionized contributes to the conductivity.

A comparison of the degrees of ionization of different substances in aqueous solutions shows that: Of the common acids, those known as the most active are ionized to more than 70 per cent in normal solutions; while feeble acids, such as carbonic, are ionized to less than one per cent. Potassium hydroxide is ionized 77 per cent, and sodium hydroxide 73 per cent. Most salts show an ionization of between 50 and 80 per cent.[2]

From the foregoing we must conclude that a solution of several different compounds capable of ionization consists of a mixture of numerous molecules, some corresponding in composition to the substances in solutions, others in greater or smaller numbers, according to concentration and the character of the substances, corresponding in composition to the ions into which some of the substances may split up.

The mobility of all the molecules of a liquid solution determines its liquidity or viscosity. Nevertheless, when the molecular mobility is so slight that the mass behaves as a solid, the solution may still retain sufficient molecular mobility to allow

[1] Smith, Alexander, *Loc. cit.*, p. 326.
[2] *Ibid*, p. 332.

ionic diffusion to take place in response to an electric current as shown by the electrical conductivity of heated rock glasses.[1] Such glass must possess a molecular constitution similar to that of a liquid solution, and distinct from that of a crystallized body, which is also indicated by the isotropism of all its physical characters. The various kinds of molecules in a glass must have no regular geometrical arrangement, but must occupy all possible positions or orientations with respect to one another. This is not the case with a mixed crystal of several isomorphous compounds, though this has been called a solid solution. For a regular geometrical arrangement or molecular structure is a characteristic of crystals.

Colloids are substances that behave quite differently toward aqueous solution from ordinary soluble substances. They diffuse with extreme slowness, or not at all; do not affect the freezing-point, boiling-point, or vapor-tension of the liquid in which they may be. They do not pass through an animal membrane as most solutions of salts do, but permit salts or other substances in solution to diffuse through them. They appear to be finely divided, minute particles of material in suspension in a liquid, and not actually in solution. Such a mechanical mixture is sometimes called a COLLOIDAL SOLUTION.

Several subtances occurring in rock magmas are known to assume the colloidal condition by uniting with hydroxyl (OH). They are silicon, aluminium, and trivalent iron, yielding $Si(OH)_4$, $Al(OH)_3$, $Fe(OH)_3$. Upon drying they become $SiO_2$, $Al_2O_3$, and $Fe_2O_3$. The possible application of these reactions to the crystallization of certain rock minerals will appear in Chapter IV.

## CHEMICAL REACTIONS IN SOLUTIONS

In order to discuss the chemical reactions that are likely to take place within a liquid rock magma, it is necessary to note some general principles that appear to underlie chemical reactions among the native elements and their compounds. It will be assumed, however, that the most elementary laws of chemistry

[1] Barus, C., and Iddings, J. P. Am. Jour. Sci., vol. 44, 1892, pp. 242–249. See also on dissociation and electrical conductivity of fused minerals, Doelter, C. Uber die Dissoziation der Silikatschmelzen. Sitzunst. d. k. Akad. d. Wiss. in Wien. Math. Naturw. Kl. vol. 116, part 1, 1907, pp. 1244–1309.

are already in mind, such as: the law of definite proportions, and that of multiple proportions in the combination of elements; the law of combining weights; the conception of valence; and the idea of the relative chemical activity of elements with respect to one another.

**Chemical Energy.**[1] — For the purposes of the present discussion we may begin with the definition of chemical energy, assuming with Ostwald that "energy is work and every other thing which can arise from work and be converted into work," or, expressing it more concisely, energy is the power of doing work; CHEMICAL ENERGY may be defined as that energy which exists within a substance, element or compound, and, upon a combination or dissociation of elements or compounds, manifests itself in changes of temperature, electricity, or of light.

**Chemical Activity** is measured and expressed in terms of the chemical energy liberated or locked up in a particular chemical reaction. And it has been found that actions involving a relatively large loss of chemical energy, and, therefore, a considerable liberation of heat or of electricity, proceed rapidly; that is, a large proportion of the material is changed in a unit of time. The relative chemical activity of several substances toward another may be reckoned in terms of the speed of a chemical change, as well as by measuring the heat developed, or the electromotive force generated under proper conditions. It is well known that the chemical activity of a given substance is not the same toward all other substances. Thus, iron unites more quickly with chlorine than with sulphur, and from a given amount of iron more heat is liberated in the first case than in the second; while with sodium it does not unite at all.

**Conditions Changing Speed of Chemical Action. Temperature.** — A change of temperature modifies notably the rate at which a chemical action takes place. A rise of temperature increases the speed of all chemical interactions. In general it may be said, that on an average, other things being equal, an increase of ten degrees in temperature doubles the amount of material changed per second, and conversely.

[1] The following statements regarding chemical reactions are derived largely from Alexander Smith's Introduction to General Inorganic Chemistry, New York, 1906, to which the student is referred for greater detail.

**Concentration** is another factor effecting a change of chemical activity. Thus the speed of interaction of a body, when other conditions are constant, is directly proportional to its concentration, that is, the closeness of the particles of the substance in the region of action. In the case of a gas, for example, when oxygen at 700 degrees is compressed in contact with barium oxide, it unites with it to form barium dioxide; but when the pressure is reduced to a partial vacuum, oxygen is liberated, and the dioxide is reduced to monoxide.

**A catalytic agent** is another factor in modifying the speed of chemical activity. A CATALYTIC agent is a substance which promotes a chemical change, or interaction between two substances, without itself suffering any permanent change. The change may be of a positive, accelerating, or of a negative, retarding, character. Water vapor in small traces promotes the chemical action of oxygen with many of the elements, which show no tendency to unite with carefully dried oxygen, even when they are strongly heated. In fact, *water is to be regarded as one of the commonest catalytic agents.* Only a few cases of retardation of chemical activity by catalytic agents are known.

**Solution,** especially in water, is a factor in effecting a change of speed in chemical action, usually promoting it greatly, but not always. The most pronounced action is effected through the *ionization* of one or both substances. The chemical behavior of ionic substances will be discussed later on. Substances whose chemical interaction is promoted by solution in water are acids, bases, and salts. Many substances are less active chemically when dissolved in water, as, for example, sugar. Moreover, most solvents, if they effect chemical change at all, retard it.

**Chemical Behavior of Ionic Substances.** — Since Barus has shown that rock magmas are electrolytes, that is, contain ionized substances, it is important to note what is known of the chemical behavior of ions in solutions.[1] First, it may be noted that solutions of ionogens are mixtures in that they contain molecules of the solvent, of the dissolved substance, and the ions of the dissociated substance. And these ions are generally the most active parts of the solution chemically. When the ionogen is a complex

[1] Smith, Alexander. Introduction to General Inorganic Chemistry, 1906, p. 334, *et seq.*

compound containing several base-forming elements or radicals, each of these becomes a distinct kind of ion. So that from a compound like some amphiboles there may be more than four or five kinds of ions in one solution of it. Each kind of ion in a solution has its own physical and chemical properties and behaves in many ways as though it were alone in the solution. The ions of salts may be simple, composed of one element, or complex, consisting of two or more. By chemical reaction between ions in solution a complex ion may be reduced to one of simpler composition, or may become more complex; or it may be converted into a compound molecule. The elements that can form simple, positive ions are known in chemistry as metals. In some cases non-metals, like nitrogen, may be present in complex positive ions, as in $NH_4$. Metals may be present in complex negative ions, usually associated with oxygen, as in $AlO_2$.

**Chemical Action Between Two or More Salts in Solution.** — When two salts are ionized in a solution there is interaction between the positive and negative ions of each. Thus if NaCl and $KNO_3$ are in aqueous solution together, there are possible, besides the first two pairs of ions, $Na^{\cdot}$, $Cl'$ and $K^{\cdot}$, $NO_3'$, two other pairs, namely, $Na^{\cdot}$, $NO_3'$ and $K^{\cdot}$, $Cl'$, so that the reversible actions involved may be represented as follows:

$$\begin{array}{rcl} NaCl & \leftrightarrows & Na^{\cdot} \quad + Cl' \\ KNO_3 & \leftrightarrows & NO_3' + K^{\cdot} \\ & & \quad\updownarrow \qquad \updownarrow \\ & & NaNO_3 \;\; KCl \end{array}$$

This is known as DOUBLE DECOMPOSITION of the salts in solution; and when the solution is dilute with respect to each possible salt, it is like a physical mixture of them, for there is no noticeable evidence of chemical change between them.

If, however, one of the possible salts resulting from the interaction of the ions is so much less soluble in the solution than the other salts that it saturates the solution, it will begin to separate out, and the process will continue until equilibrium has been established between the various parts of the solution. For when a solid is being dissolved or precipitated, the process is a reversible physical operation involving the equilibrium

between the undissolved and dissolved substance, which may be expressed thus:

$$\text{Molecules (undissolved)} \rightleftarrows \text{molecules (dissolved)}.$$

This operation involves the molecules directly and the ions only indirectly, for they are in equilibrium with the dissolved molecules. That is, when a solid dissolves, it does so in molecular form, the ions developing subsequently until equilibrium is reached. This is expressed by:

$$\text{Molecules (undissolved)} \rightleftarrows \text{molecules (dissolved)} \rightleftarrows A^{\cdot} + B'.$$

When molecules separate from solution, equilibrium between dissolved molecules and ions is disturbed, resulting in the uniting of ions to form more molecules. If the ions, which can form molecules that are separating from the solution, are supplied by the dissociation of other molecular compounds, salts, in solution, this action will continue until all of the molecules capable of being formed in this way in excess of what the liquid can hold in solution have been separated in a solid form, precipitated. A familiar example is that of NaCl and $AgNO_3$, whose interaction is represented as follows:

$$\left.\begin{array}{l} NaCl \leftrightarrows Na^{\cdot} \;\; + Cl' \\ AgNO_3 \leftrightarrows NO_3' + Ag^{\cdot} \\ \qquad\quad\;\; \uparrow\downarrow \\ \qquad\quad NaNO_3 \end{array}\right\} \leftrightarrows AgCl \text{ (dissolved)} \leftrightarrows AgCl \text{ (solid)}.$$

**Hydrolysis of Salts.** — Hydrolysis is a double decomposition involving water, and necessitates the slight ionization of water. While naturally water is but very slightly ionized, and the presence of its ions in an aqueous solution may be neglected, there are cases in which the chemical behavior of its ions must be reckoned with. Compare the catalytic action of water. The ionization of water results in hydrogen ions, $H^{\cdot}$, and hydroxyl ions, $OH'$, and each of these combining with the electrically opposite ion of a dissolved salt forms a small amount of base and acid in solution. If one of these compounds, base or acid, is much more readily ionized than the other, the ionic equilibrium will be disturbed to the extent that the less ionized compound will withdraw hydrogen ions, or hydroxyl ions, from

the solution, making it possible for more to separate from the water until a noticeable amount of the more ionizable pair, acid or base, exists in the solution, producing an acid or alkaline character as the case may be. Consequently hydrolysis is more noticeable when the salt is compounded of an acid and base of very different degrees of activity, whether it is the acid or the base that is the weaker. In the first case the result of the hydrolysis is a basic, alkaline, reaction; in the second, an acid reaction. Other things being equal, salts containing *bivalent* or *trivalent* radicals are more noticeably hydrolyzed than are those composed only of univalent radicals.

In aqueous solutions, then, it is necessary to add to the ions of the dissolved compound those of the solvent, water. When a solution is considered a mutual solution of two or more substances the ions involved in its proper discussion are all those capable of forming from its ionizable components.

**Acids, or Hydrogen Salts.** — Compounds like $HCl$ and $H_2SO_4$ are commonly called acids, but their acid properties are only exhibited when ionized in water or some other ionizing solvent, and then the acid properties are found to belong wholly to the hydrogen ion, $H^{\cdot}$. The compounds in question are salts of hydrogen, in which hydrogen plays the rôle of a metal. Hydrogen salts upon ionization always yield positive hydrogen ions, $H^{\cdot}$, just as all potassium salts yield positive potassium ions, $K^{\cdot}$. The negative ions from similar salts of hydrogen or potassium are alike in each case.

Generally hydrogen salts exchange radicals with the other ionogens; often, even, when dissolved in non-dissociating liquids. They frequently do it also in the absence of a solvent, especially when heated. They are differently soluble in water and give acids of very different activity.

**Ionization of Acids.** — The number of kinds of ions derivable from an acid, or hydrogen salt, varies with the units of hydrogen in its molecule. Those with only one of hydrogen can yield only two kinds of ions, such as $HCl \leftrightarrows H^{\cdot} + Cl'$. Those with two units of hydrogen may furnish three kinds. Thus $H_2SO_4$ may produce $H^{\cdot} + HSO_4'$, and $HSO_4$ may yield $H^{\cdot} + SO_4''$.

$$H_2SO_4 \leftrightarrows H^{\cdot} + HSO_4' \leftrightarrows H^{\cdot} + SO_4''.$$

$HSO_4'$ is an acid which is less active than $H_2SO_4$ and is therefore less ionized in aqueous solution. Consequently in concentrated solutions of $H_2SO_4$ there is much $HSO_4'$ and little $SO_4$," but in very dilute solutions $SO_4''$ predominates. This behavior is common to all acids containing more than one hydrogen unit in the molecule. It must then apply to orthosilicic acid, $H_4SiO_4$, with four units of hydrogen.

**Chemical Activity of Acids.** — The activity of an acid, or hydrogen salt, depends upon the extent to which water is able to ionize it, for the greater the ionization the greater the number of hydrogen ions developed in a given amount of solutions containing equivalent quantities of hydrogen salts, that is, the greater the concentration of hydrogen ions. And as already pointed out, the chemical activity of any substance depends on its concentration. Since hydrogen salts differ greatly in the extent to which they may be ionized in aqueous solution they furnish acids of very different degrees of activity. When a hydrogen salts is but slightly soluble in water, as is the case with silicic acid, $H_4SiO_4$, there can be but very slight concentration of ions in an aqueous solution of silicic acid.

**Bases, or Hydroxyl Salts.** — Compounds like $K(OH)$ and $Mg(OH)_2$ are commonly called bases, but their basic properties are exhibited only when in solutions in which ionization has taken place, and the peculiar characteristics of bases are wholly attached to the hydroxyl ion, $OH'$, so that such compounds should be considered as salts of a metal or of some electrically positive radical, as in the case of $NH_4OH$, in which hydroxyl is the negative radical.

Generally salts of hydroxyl undergo double decomposition with other ionogens, even in the absence of solvents, and since they are ionized to different extents in solutions of equivalent concentration, and yield different concentrations of hydroxyl ions, their solutions exhibit different degrees of basic activity. The common hydroxyl salts, except those of potassium, sodium, barium, strontium, calcium, and ammonium, are very slightly soluble in water.

**Ionic Double Decomposition between Acids and Salts, and between Bases and Salts.** — The interaction is similar to that which takes place between two salts as already described, for the

acid may be considered a hydrogen salt, and the base in turn a hydroxyl salt. When a highly dissociated acid and salt are mixed there is a reversible action leading to the production of another acid and salt. Thus

$$\begin{array}{rcl} H_2SO_4 \rightleftarrows & 2\,H^{\cdot} & + \; SO_4'' \\ 2\,NaCl \rightleftarrows & 2\,Cl' & + \; 2\,Na^{\cdot} \\ & \uparrow\downarrow & \quad \uparrow\downarrow \\ & 2\,HCl & \quad Na_2SO_4 \end{array}$$

If the new compounds are as highly ionized as the first, there is no marked change in the mixture. If there is a notable change in the ionization, though all of the compounds may remain in solution, the changed condition of the solution will be recognizable in its electrical conductivity. If one of the new compounds is considerably less soluble than the first, it may saturate the solution and separate from it by precipitation.

When a base and a salt are mixed in a solution, the interaction is analogous to that just described for an acid and base. There will tend to form a new base and salt.

**Ionic Double Decomposition and Chemical Activity** of the free substances are not directly related to one another, for the precipitation of a salt, acid, or base, depends wholly on the solubility of the compound, and not on the degree of activity of the ions, since relatively inactive ions may form slightly soluble compounds in the presence of more active ions and their compounded molecules.

**Double Decomposition between Acids and Bases. Neutralization.** — When an acid and a base react on one another in solution, the ionic interchange almost always continues until a complete exchange has taken place, resulting in a salt, composed of the positive metal, or radical, of the base and the negative element, or radical, of the acid, besides water, the compound of the negative radical, OH′, of the base and the positive element, $H^{\cdot}$, of the acid. Thus

$$NaOH + HNO_3 \rightarrow NaNO_3 + H_2O.$$

When equivalent quantities of acid and base are combined, the result is a mixture with neither acid nor basic properties, since all of the hydrogen ions and hydroxyl ions have combined to form

$H_2O$. Its behavior being neutral in this respect, the action is called NEUTRALIZATION.

**Mixed Ionogens and Double Salts.** — When a negative ion is univalent, as $Cl'$, it generally unites with but one kind of positive ion, giving a simple salt, called NORMAL, or NEUTRAL, SALT, such as KCl. In this case the acid is said to be *monobasic*. When the ion has a higher valence several different cases may arise, which are illustrated as follows:

| From $CO_3''$ | | From $Fe^{\cdot\cdot}$ | |
|---|---|---|---|
| $H_2CO_3$ | acid | $Fe(OH)_2$ | base. |
| $K_2CO_3$ | normal salt. | $FeSO_4$ | normal salt. |
| $KHCO_3$ | acid salt. | $Fe(OH)SO_4$ | basic salt. |
| $KNaCO_3$ | mixed salt. | $Fe_2Cl_2SO_4$ | mixed salt. |

In acid salts only part of the hydrogen has been replaced by a metal or a positive radical. It may, or may not, exhibit an acid reaction when in solution. If the hydrogen ions are too few, its action may be neutral. The same is true of basic salts. They may not show a basic reaction in solution. On the other hand a neutral salt may give an alkaline reaction because of hydrolysis. The names ACID, BASIC and NEUTRAL are used to indicate the character of the composition of a salt, and not its reaction when in solution. Mixed salts, when they may be considered as made up of two salts, $2\ KNaCO_3 = K_2CO_3 + Na_2CO_3$, are sometimes called DOUBLE SALTS.

The foregoing statements concern the dissociation and combination of ions. There are other ways in which ionic chemical changes may be effected. One is the displacement of the material of one ion by another substance, through the withdrawal of the first. Another is the destruction or formation of a compound ion, by chemical action on it. Another affects the electrical charges of two ionic materials.

**Displacement of one Ion.** — When a metal like zinc is placed in dilute acid, hydrogen is liberated and the ionic change is expressed by

$$Zn + 2\ H^{\cdot} \rightarrow Zn^{\cdot\cdot} + H_2.$$

Hydrogen escapes and zinc would be recovered from solution as a zinc salt of the acid used. Zinc will displace ions of iron, lead, copper and silver, but not those of calcium, and potassium.

When all metals are investigated in this respect, they are found to fall into a series in which each metal is capable of displacing all metals following it in the series. This is known as the ELECTROMOTIVE SERIES of the metals, for it corresponds to the varying electromotive force required to deposit each metal from a normal solution of the salts of each metal. Those metals most commonly met with in rock magmas are shown in their electromotive series, beginning with the strongest, potassium. The order in this series also corresponds to their chemical activities in a free state toward other elements. This is well illustrated by their behavior toward oxygen. The first elements in the series combine readily with oxygen, while the last in the series do not. The same relative activities must be shown toward silicon and its acid radicals. The negative acid-forming elements and ions can be arranged in a similar manner.

ELECTROMOTIVE SERIES

Potassium
Sodium
Lithium
..............
Calcium
Magnesium
Aluminium
Manganese
..............
Chromium
..............
Iron
Cobalt
Nickel
..............
Hydrogen
..............
..............
Platinum
Gold

As stated by Smith "It must be noted that the electromotive series has no bearing on the tendency of one radical to dislodge another in double decompositions. The place of an element in this series defines its relative activity, *when free*, and has to do only with actions where one *free element displaces* another." [1]

[1] *Loc. cit.* p. 362.

# CHAPTER IV

## CHEMICAL REACTIONS IN ROCK MAGMAS

**Introduction.** — In discussing the chemical and physical behaviors of molten rock magmas, it is possible to begin with the consideration of the chemical reactions which may be reasonably expected to take place if the chemical elements known to occur in igneous rock were brought within reach of one another at temperatures and pressures likely to obtain within the earth. For the compounds — minerals — formed in igneous magmas are inorganic, and may be produced in the laboratory by the interaction of the constituent elements at proper temperatures, and under conditions favorable to their crystallization. And since the relative proportions of the elements so brought together must affect the character of the resulting compounds, and as there are many possible variations in these proportions in different kinds of igneous rocks, it is necessary to select some particular case as a basis for the discussion. For reasons which will appear in the sequel the composition of an average of all known igneous magmas may be advantageously chosen. The possible average analysis as estimated by Clarke has already been cited on page 24. Leaving out of consideration for the present the elements occurring in very small amounts, with the exception of those that are commonly noted in pyrogenetic minerals, the relative proportions of the elements by weight are given in column I; their relative proportions by atoms in column II.

| | | I. Percentage weights. | II. Atomic proportions. |
|---|---|---|---|
| Oxygen | O | 47.09 | 2.943 |
| Phosphorus | P | .11 | .003 |
| Silicon | Si | 28.23 | .994 |
| Titanium | Ti | .43 | .009 |
| Zirconium | Zr | .03 | .000 |
| Aluminium | Al | 7.99 | .294 |
| Ferric iron | $\dddot{Fe}$ | 1.81 | .032 |
| Ferrous iron | $\ddot{Fe}$ | 2.64 | .047 |
| Magnesium | Mg | 2.46 | .101 |
| Calcium | Ca | 3.43 | .085 |
| Sodium | Na | 2.53 | .109 |
| Potassium | K | 2.44 | .062 |
| Hydrogen | H | .17 | .168 |
| Remainder | | .64 | |
| | | 100.00 | |

From this it is seen that three-fifths of the whole, atomically, is oxygen, an active element capable of combining with all the other elements under consideration, with which it may enter acid or basic radicals, forming compounds known as salts; or it may form oxides, according to the kinds and proportions of the other elements. These elements belong to several chemical groups, the members of which often behave very much alike. They are: (1) phosphorus; (2) silicon, titanium, zirconium; (3) aluminium, ferric iron; (4) ferrous iron, magnesium, calcium; (5) sodium, potassium; (6) hydrogen.

PHOSPHORUS, though in very small amount, is so universally present in rock magmas that it should enter into the discussion. Since it possesses several valencies, it combines with oxygen in a number of ways, and may form four different acids; orthophosphoric acid being $H_3PO_4$. This is a stronger acid than most other acids with which it is associated in rock magmas. The salts of this acid with the strongly basic, alkali elements are not stable compounds, being soluble in water, but the next active base-forming element in the series, calcium, forms with it a more stable salt, and orthophosphoric acid is known to form a very stable complex salt with calcium and a basic fluorine radical (CaF), sometimes a chlorine radical (CaCl). This is $(CaF)Ca_4(PO_4)_3$; when crystallized it is fluor-apatite, whose melting point at atmospheric pressure is from 1270° to 1300° C. This compound may exist in very small quantities in liquid rock magmas of an average composition.

SILICON constitutes nearly one-fifth of the average magma atomically, and is next in importance to oxygen. It is a non-metallic element with constant valence, and combines with oxygen to form several kinds of silicic acids and their corresponding salts, or to form simply an oxide, $SiO_2$.

While silicon resembles carbon in some respects, it differs from it in not occurring in a free state as carbon frequently does; it is fusible at a very high temperature; and at high temperatures it seems to be more active chemically than carbon, since it will displace carbon from a salt such as potassium carbonate when in a fused condition. Silicon also differs from carbon notably in that it combines with hydrogen in only two well-defined compounds. The hydride $SiH_4$ is decomposed on heating. Silicon dioxide, $SiO_2$, though differing markedly from $CO_2$ in physical characters, behaves much like it chemically, and will displace carbon dioxide from alkali carbonates at high temperatures.

**Silicic Acid** is so difficultly soluble in water that little is known of its characters by laboratory observation in aqueous solutions. It may be separated from a solution of alkali silicate, such as $Na_4SiO_4$, presumably as $H_4SiO_4$; more correctly as $SiO_4''''$ ions, which are supposed to unite with hydrogen ions, $4H^{\cdot}$, to form orthosilicic acid, $H_4SiO_4$. But in this process it separates as a gelatinous precipitate, $Si(OH)_4$. Upon drying, this compound loses water gradually, until it finally reaches an anhydrous condition, as $SiO_2$. During this transition from a composition corresponding to that of orthosilicic acid it passes through stages in which it has the composition of meta-, poly-, and disilicic acids, as indicated by the following:

$$
\begin{aligned}
H_4SiO_4 \quad &= H_4SiO_4 \text{ orthosilicic acid} \\
H_4SiO_4 - H_2O &= H_2SiO_3 \text{ metasilicic acid} \\
3\,H_4SiO_4 - 4\,H_2O &= H_4Si_3O_8 \text{ polysilicic acid} \\
2\,H_4SiO_4 - 3\,H_2O &= H_2Si_2O_5 \text{ disilicic acid}
\end{aligned}
$$

If these represented definite compounds during the process of drying there should be steps in the changes of vapor tension of the water corresponding to these definite stages of composition. But nothing of the sort is observed. The existence of these acids is inferred from the definite and stable character of numerous silicate compounds.

The behavior of the precipitated silicon jelly with respect to vapor tension is analogous to its behavior with regard to osmotic pressure and freezing point, and indicates that the substance is in a *colloidal* condition. That is, a condition in which it is not in solution, or a part of the liquid, but is in a finely divided, solid state, capable of remaining in suspension in the liquid under some conditions, or of settling with some of the liquid mixed with it. From this it is evident that compounds having the composition of the silicic acids are but very slightly soluble in water under the conditions of temperature and pressure ordinarily accompanying laboratory investigations. It may be further assumed that substances in a colloidal state are less active chemically than they would be if dissolved in any liquid.

A molten rock magma is not primarily an aqueous solution although the constituents of water are parts of it, and transitions from a magma very poor in water to those which may contain much of it undoubtedly exist. In the magma represented by the average analysis under consideration, water forms only 1.5 per cent, and the oxidized silicon may be

imagined as combining directly with other constituents so far as possible without the intervention of water.

Such combinations have been effected repeatedly in the laboratory by heating together the elements given in an analysis, and the resulting compounds have in many cases the same composition and physical characters as rock minerals. Frequent reference will be made to the results of these synthetical investigations, but no attempt will be made to rehearse them at length. The student will find them described in the publications of Fouqué and Michel-Lévy,[1] Doelter,[2] Vogt,[3] Day,[4] Morozewicz,[5] and others.

A study of these laboratory productions as well as of igneous rocks themselves shows that salts of several different silicic acids form by the side of one another, their character and abundance depending on the nature of the basic elements present in the mixture, and on their proportions. Orthosilicates, metasilicates, and polysilicates commonly form in the presence of one another; sometimes accompanied by uncombined, or free, silicon dioxide. And it is evident that the formation of the different kinds of acid ions, or their salts, is controlled primarily by the strength, or chemical activity, of the base-forming elements; is dependent also on the amount of silicon available in the solution, and may be modified, of course, by other factors. This will appear in the tabulated statement below.

Of the base-forming elements uniting with silicic acids in the mixture of the average magma *aluminium* is in greatest atomic abundance. It is, however, the weakest in its basic, or acidic, behavior, being capable of playing the rôle of acid toward a strong base, or that of a base toward a strong acid.

It is to be noted that aluminium does not combine with silicic acid alone in these mixtures under most conditions attending the formation of igneous rocks, or not to any appreciable extent, but always enters a molecule with other basic elements.

[1] Fouqué, A., and Michel-Lévy, A. Synthèse des Minéraux et des roches Paris, 1882.

[2] Doelter, C. Allgemeine chemische Mineralogie, 1890, and numerous publications in Neues Jahrb. Min. Petr., etc., and in Tscher. min. petr. Mitth.

[3] Vogt, J. H. L. Die Silikatschmelzlösungen, etc. Videnskabs-Selskabets Skrifter, I Math.-naturv. Klasse, 1903, No. 8; and 1904, No. 1.

[4] Day, A. L., et alia, numerous publications in Am. Jour. Sci. and in Publications, Carnegie Institution, Washington.

[5] Morozewicz, J. Tscher. min. petr. Mitth., vol. 18, 1898, pp. 1–90, and 105–240.

These elements are: (1) potassium and sodium; (2) calcium; (3) magnesium and iron. Potassium and sodium are the most active base-forming elements; calcium is less so; and magnesium and iron are still less active chemically. This sequence accords with their behavior in other respects, as in the electromotive series. The difference in the tendencies of aluminium to associate itself with the different elements just named is so marked, and some of its combinations are so definite and invariable, that the relationships in question become significant of the relative strengths of combination, or of affinities, among these particular elements under the conditions of fusion assumed. The same has been said of the relation between these elements and the various silicic acids, and the relationships will be illustrated by the simplest salts commonly forming in these mixtures. From these simple compounds the discussion can proceed to the more complex.

**Common Simple Silicates.** — The following are the commonest simple silicate salts that form in rock magmas; also different expressions for the silicic acids, and their negative radicals.

SILICIC ACIDS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Orthosilicic | $H_4SiO_4$ | or | $H_4SiO_4$ | or | $H_4(SiO_4)$ | $\equiv$ | $(SiO_4)$ |
| Metasilicic | $H_2SiO_3$ | | $H_4Si_2O_6$ | | $H_4(SiO_3)_2$ | $\equiv$ | $(Si_2O_6)$ |
| Polysilicic | $H_4Si_3O_8$ | | $H_4Si_3O_8$ | | $H_4(Si_3O_8)$ | $\equiv$ | $(Si_3O_8)$ |
| Disilicic | $H_2Si_2O_5$ | | $H_4Si_4O_{10}$ | | $H_4(Si_2O_5)_2$ | $\equiv$ | $(Si_4O_{10})$ |

| POLYSILICATES. | METASILICATES. | ORTHOSILICATES. |
|---|---|---|
| $\left.\begin{matrix}K-\\Al\equiv\end{matrix}\right\}Si_3O_8$ (orthoclase) $\left.\begin{matrix}Na-\\Al\equiv\end{matrix}\right\}Si_3O_8$ (albite) | $\left.\begin{matrix}K-\\Al\equiv\end{matrix}\right\}Si_2O_6$ (leucite) | $\left.\begin{matrix}Na-\\Al\equiv\end{matrix}\right\}SiO_4$ (nephelite) |
| | | $\begin{matrix}Al\equiv\\Ca=\\Al\equiv\end{matrix}\begin{matrix}SiO_4\\ \\SiO_4\end{matrix}$ (anorthite) |
| | $\left.\begin{matrix}Ca=\\(Mg, Fe)=\end{matrix}\right\}Si_2O_6$ (diopside) | |
| | $(Mg, Fe_2)\equiv Si_2O_6$ (hypersthene) | $(Mg, Fe)_2\equiv SiO_4$ (olivine) |

In these salts it will be noted that the highest silicic acid of the three, polysilicic, or trisilicic, is united only with the strongest base-forming elements, potassium and sodium; and further that the stronger of the two, potassium, may also form a normal metasilicate, whereas sodium does not form one of common occurrence (p. 128), but may form an orthosilicate. It is also notable that in these compounds aluminium is combined in the definite atomic ratio to the alkali of 1 : 1. When it is remembered that potassium is the strongest base-forming element and that silicic acid is a comparatively weak acid, though polysilicic acid is probably stronger than meta- and orthosilicic acids, the rôle of aluminium in these compounds is in doubt. Does it belong with the negative, acid radical, or with the positive, basic radical? Whatever its rôle, it is never in variable proportions with either the alkali or the silicon in these molecules, which are definite and fixed. Certain variations in the orthosilicate molecule, nephelite, have been discussed in another place. Aluminium enters an orthosilicate with calcium, the two being in the definite atomic ratio of 2 : 1.

All of these five salts may form from one solution and occur together in some igneous rocks when the elements in the solution are in proper proportions. If, however, they are not in sufficient amounts, but there should be insufficient aluminium to form all five salts, other things being constant, then the relative affinities between the other base-forming elements and aluminium show themselves. And it appears that the potassium and sodium will combine with aluminium to the exclusion of calcium. And when there is insufficient aluminium to satisfy all the alkalies, then potassium combines with it in preference to the sodium. The strongest base-forming element appears to exert the strongest control over the aluminium.

As to the formation of the different silicates of the alkalies and aluminium, it has been observed in igneous rocks and in laboratory synthesis that the highest silicate, polysilicate, forms when there is sufficient silica in the solution, and that the meta- and orthosilicates of these elements form only when the available silica is insufficient to form the polysilicates. They do not form in the presence of free silica. Furthermore, of the two alkalies, potassium has the stronger control of the silicic

acid, for if there is insufficient silicon to form both the potassium and sodium polysilicate salts it is the sodium that enters the lower silicate, in this case an orthosilicate, while the potassium forms the polysilicate; moreover, the potassium metasilicate does not form in the presence of the pure sodium polysilicate, though it does form when the latter salt is in the control of its isomorphous calcium-aluminium silicate, a condition discussed at length on p. 134. The relative strength of the alkalies and calcium toward aluminium and the silicic acids having been indicated, it remains to point out their relative strengths as compared with magnesium and ferrous iron as shown by the remaining common silicate salts.

Comparing calcium with magnesium and ferrous iron, it is to be noted that calcium commonly forms with magnesium and iron a metasilicate, the atomic ratio between the calcium and the other two basic elements in the great majority of cases being 1 : 1. Smaller proportions for the calcium have been noted in some cases. Moreover, calcium does not form a simple metasilicate in igneous rocks, except possibly in rare instances, whereas magnesium and ferrous iron commonly form a metasilicate free from calcium. They also form the orthosilicate, usually when there is insufficient silicic acid to form the metasilicate, but to this there are notable exceptions to be discussed in another place. Calcium does not enter this orthosilicate, nor does it form one by itself in igneous rocks. It occurs in several aluminous orthosilicates, one of which, anorthite, has already been discussed; the others are not so common. From these facts it appears that calcium has a stronger hold on silicic acid than magnesium and ferrous iron, which may form orthosilicates by the side of calcium metasilicates.

As to the relative strengths of the alkalies toward silicic acid as compared with that of magnesium and ferrous iron, it is shown by the formation of polysilicates to be stronger, and when there is insufficient silicon to form polysilicates of the alkalies and metasilicate of magnesium and iron, it is the latter that form the lower silicates rather than the alkalies. Thus orthosilicate of magnesium and iron, olivine, forms in association with polysilicates of the alkalies, orthoclase, albite, but the metasilicate of magnesium and iron, hypersthene, does not form

in association with meta- and orthosilicates of the alkalies, leucite, nephelite.

As between magnesium and ferrous iron, the former exhibits the stronger control over silicic acid in igneous rocks, for magnesium rarely forms a compound free from silicic acid, while iron commonly does, occurring as an oxide, hematite, and as a ferrate, magnetite.

While the above method of expressing the chemical relationships between the elements in the solution under discussion is entirely justified when the problem is considered from the point of view assumed, it is probable that, when the behavior of the compounds is viewed in the light of certain physico-chemical phenomena, other modes of expression will be found to be more fitting.

Having considered the most fundamental relationship between the commonest elements in igneous rocks as it may be illustrated by the simplest cases, a discussion of more complex relations and in some cases less simple compounds will be in order.

**Alkali-Aluminium Silicates.** — The potassium-sodium-aluminium silicates just discussed are not the only ones that form in rock magmas, or the only ones that might be expected to form. Lithium is noted in traces in many igneous rocks, and occurs in notable amounts in certain varieties of them. It forms isomorphous compounds with potassium and sodium in some instances, and the analogies and differences between these compounds furnish an interesting field for physico-chemical investigation. The following mineral compounds are known, but are not all pyrogenetic:

| DISILICATE. | POLYSILICATE. | METASILICATE. | ORTHOSILICATE. |
|---|---|---|---|
| | $\left.\begin{matrix} K- \\ Al\equiv \end{matrix}\right\} Si_3O_8$ (orthoclase) | $\left.\begin{matrix} K- \\ Al\equiv \end{matrix}\right\} Si_2O_6$ (leucite) | $\left.\begin{matrix} K- \\ Al\equiv \end{matrix}\right\} SiO_4$ (kaliophilite) |
| | $\left.\begin{matrix} Na- \\ Al\equiv \end{matrix}\right\} Si_3O_8$ (albite) | $\left.\begin{matrix} Na- \\ Al\equiv \end{matrix}\right\} Si_2O_6$ (jadeite) | $\left.\begin{matrix} Na- \\ Al\equiv \end{matrix}\right\} SiO_4$ (nephelite) |
| $\left.\begin{matrix} Li- \\ Al\equiv \end{matrix}\right\} Si_4O_{10}$ (petalite) | | $\left.\begin{matrix} Li- \\ Al\equiv \end{matrix}\right\} Si_2O_6$ (spodumene) | $\left.\begin{matrix} Li- \\ Al\equiv \end{matrix}\right\} SiO_4$ (eucryptite) |

The disilicate is petalite, formed in pegmatite magmas with polysilicates, orthoclase, albite, and with the metasilicate of lithium and aluminium, spodumene; usually in the presence of free silica, quartz. Why are there no corresponding disilicates of potassium and sodium? On the other hand, there is no lithium aluminium polysilicate, which might accompany the polysilicates, orthoclase and albite. Of the metasilicates, the potassium salt, leucite, is well known in certain kinds of rocks comparatively low in silica, whereas the corresponding lithium compound, spodumene, is equally well known in rocks rich in free silica. The two minerals are not isomorphous, however. The sodium compound, jadeite, is extremely rare as a mineral, and is of uncertain origin. But a hydrated compound, analcite, is sometimes pyrogenetic, and has the same crystal habit as leucite, the potassium compound. As orthosilicate compounds the three alkalies are known to form crystals belonging to the same system, hexagonal. But only the sodium compound, nephelite, forms in rock magmas, the other two being secondary minerals. The potassium mineral, kaliophilite, has been formed by contact metamorphism whereby it appears as though the calcium of a carbonate partly reduced the metasilicate molecule leucite, depositing the orthosilicate in the block of metamorphosed limestone (Mte. Somma). The lithium mineral, eucryptite, has been formed from the metasilicate, spodumene, by a process of dissociation into ortho- and polysilicate, albite, (Branchville).

It is further to be noted that the nephelite that forms in rock magmas always contains some potassium (Na : K :: 4 : 1 to 5 : 1). But this does not enter as an isomorphous orthosilicate, for the silicon is always too high, and it has been suggested that there is a mixture of a potassium-aluminium metasilicate, or a potassium-natrolite compound, with the sodium compound in solid solution. This corresponds to the stronger affinity of potassium for silicon.[1]

The failure of the several compounds of these alkali elements to form alongside of one another in rock magmas is undoubtedly due to the fact that the compounds which are chemically possible, and some of which form under favorable conditions, are not equally stable under the conditions and in the chemical mixtures producing igneous rocks. The exact conditions of equlibrium for each case are not known at present.

[1] Morozewicz, J. Bull. Acad. Sci. Cracovie, 1907, pp. 958–1008.

The formation of the lithium compounds in certain kinds of rocks, sometimes on a very large scale, is due to processes of concentration of lithium molecules in these magmas, and in the case of the lithium micas there is an excess of silicon over that found in the analogous potassium micas.

**Sodalites. Mixed Salts.** — Several compounds, closely related to nephelite chemically, and commonly associated with it in igneous rocks, may be mentioned in this place. They are mixed orthosilicate salts of sodium and aluminium containing small amounts of chlorine in one case, and of sulphur in two, with some calcium in one compound. They appear to form under nearly the same conditions as those determining the production of nephelite, that is to say, relatively low silicon content of the magma, with the additional condition that chlorine or sulphur be present in the solution. The composition of sodalite may be expressed thus:

$$Na_4(AlCl)Al_2(SiO_4)_3 \text{ . . sodalite.}$$

This is equivalent to a sodium nephelite plus sodium chloride.

$$Na_3Al_3(SiO_4)_3 + NaCl = Na_4(AlCl)Al_2(SiO_4)_3.$$

In fact the compound, sodalite, has been produced in the laboratory by heating together nephelite and sodium chloride. In a rock magma the formation of sodalite does not necessarily involve the production of nephelite molecules and their subsequent transformation into sodalite, but only requires that when the conditions are proper for the formation of nephelite there should be chlorine in the solution and sufficient sodium. The extra sodium, which enters the sodalite compound in excess of what would have been sufficient to form nephelite, in the absence of chlorine must enter other silicate molecules.

When sulphur is present, and the conditions are those controlling the formation of the orthosilicate of sodium and aluminium, nephelite, there may be formed a mixed salt which may be considered a modification of the nephelite compound, closely analogous to that of sodalite. This mixed salt varies in composition according to the amount of calcium present, and is represented by

$$Na_4(NaSO_4Al)\,Al_2(SiO_4)_3 \text{ . . . . . . . noselite.}$$
$$(Na_2,Ca)_2(NaSO_4Al)Al_2(SiO_4)_3 \text{ . . haüynite.}$$

Noselite and haüynite grade into one another chemically and physically, have similar crystal forms to those of sodalite, and commonly accompany this mineral and nephelite in igneous rocks rich in sodium and aluminium and relatively low in silicon. Like nephelite they do not form from magmas in which there is sufficient silicon to convert them into polysilicates; they do not occur with pyrogenetic quartz.

**Acid Alkali Aluminium Orthosilicates.** — The rôle of hydrogen in the chemistry of igneous rocks, whether as an active, base-forming element, or as a catalytic agent alone, H, or combined with oxygen, OH, is of the first importance, but is only imper-

fectly understood at the present time. Its full significance will become more apparent as our knowledge of the physical chemistry of rock magmas becomes more definite. A conception of its bearing on the formation and association of certain common pyrogenetic rock minerals may be derived from the following considerations.

Adopting the idea already expressed that an acid is a hydrogen salt in which hydrogen plays the rôle of a positive, base-forming element, an acid salt may be considered one in which all of the hydrogen has not been replaced by other base-forming metals, or it may be thought of as a substitution derivative from the acid. Conversely a salt in which part of the metal elements is replaced by hydrogen may be looked upon as a substitution derivative from the salt.

Such an acid salt, or substitution derivative involving hydrogen, is represented by the compound, muscovite,

$$KH_2Al_3(SiO_4)_3 \text{ or } (K,H)Al(SiO_4).$$

This might be derived by substitution from

$$3\ KAl(SiO_4),\ Al_4(SiO_4)_3, \text{ or } 3\ H_4SiO_4.$$

The formation of such a compound involves the presence of active hydrogen to play the rôle of metal, or the presence of orthosilicic acid only partly combined with a base. In igneous rocks muscovite is a common pyrogenetic mineral, oftenest formed in magmas rich in silicon, with much free silica. It also forms in rocks with comparatively low silicon accompanying the orthosilicate, nephelite. In general it forms by the side of polysilicates, orthoclase and albite, and may accompany the disilicate, petalite.

Its formation must be ascribed to the action of hydrogen upon the silicon, either directly in the first instance, or if a previously formed silicate be imagined as the source of the salt in question, then its effect must be that known as hydrolysis, whereby the hydrogen ions from water replace metals in the salt, through a process of double decomposition. (p. 116.)

It is known that the chemical activity of hydrogen, even toward a gas, like oxygen, is greatly increased by rise of temperature, hydrogen being rather inert at ordinary temperatures. It has been found impossible to produce mica in open crucibles,

from which hydrogen, or water vapor, naturally escapes at high temperatures. Moreover, muscovite is not formed pyrogenetically in surface lavas, or, if so, to a very small extent, as compared with its occurrence in rocks crystallized under considerable pressure. It is to be noted in addition that the only silicic acid which has been produced in aqueous solution is orthosilicic acid, in which silicon is combined with four molecules of hydroxyl, $Si(OH)_4$. This represents the most complete saturation of the silicon with hydroxyl, or a combination of silica with the greatest amount of water, of all the silicic acids which are represented by salts in igneous rocks, as will appear from the following:

| ORTHOSILICIC ACID. | METASILICIC ACID. | POLYSILICIC ACID. | DISILICIC ACID. |
|---|---|---|---|
| $H_4SiO_4$<br>$H_4O_2 \cdot SiO_2$<br>$SiO_2 \cdot 2\ H_2O$ | $H_4Si_2O_6$<br>$H_4O_2 \cdot 2\ SiO_2$<br>$SiO_2 \cdot H_2O$ | $H_4Si_3O_8$<br>$H_4O_2 \cdot 3\ SiO_2$<br>$SiO_2 \cdot \frac{2}{3}\ H_2O$ | $H_4Si_4O_{10}$<br>$H_4O_2 \cdot 4\ SiO_2$<br>$SiO_2 \cdot \frac{1}{2}\ H_2O$ |

Comparing potassium-aluminium polysilicate, $KAlSi_3O_8$, with hydrogen orthosilicate, $H_4SiO_4$, the greater activity of potassium is indicated by the fact that KAl combines with three silicon atoms, while $H_4$ only combines with one silicon, the aluminium being a weak base-forming element, and therefore of slight influence. Compare $NaAl(SiO_4)$, nephelite, with $H_4(SiO_4)$.

The formation of the acid orthosilicate, muscovite, in the presence of polysilicates, and even free silica, must be assigned to the chemical activity of hydrogen at high temperature, under sufficient pressure to hold it in the liquid magma solution.

There is no evidence in igneous rocks, however, that hydrogen has displaced potassium to form muscovite. When muscovite occurs there is always an excess of aluminium over potassium in the magma. Or, in other words, it does not form in magmas in which the aluminium is less than, or only just equal to, the potassium molecularly. It may even be said that it does not displace sodium, and that it does not occur in rocks in which the sum of both the alkalies is less than, or equal to, the aluminium. It does not form in magmas with acmite. Its relationship to calcium-aluminium silicates is less simple, owing to its occurrence in mixed salts, biotites, in most cases in which its molecules are associated with calcium silicates; and it may be said that pure muscovite does not occur pyrogenetically with non-aluminous calcium silicates.

**Micas. Mixed Salts.** — Isomorphous with muscovite are more complex salts, whose chemical expression has been found very difficult, and which have been interpreted in several ways. Following that suggested by F. W. Clarke, it is possible to consider the various micas that form pyrogenetically as substitution derivatives from an orthosilicate of aluminium, $Al_4(SiO_4)_3$, in which one or more atoms of aluminium may be replaced by equivalent values of univalent, bivalent or trivalent elements or radicals; the first being represented by H,K,Li,[Na] and $(MgF),(AlF_2),(AlO)$; the second by Mg,Fe[Mn]; the third by $\dddot{\mathrm{Fe}}$, [Cr]. It is possible that in the more siliceous varieties of mica there may be an admixture of $Al_4(Si_3O_8)_3$ in solid solution.

Lithium is in notable amounts in some magmas rich in silicon, alkalies and aluminium, certain granite pegmatites. In such cases it commonly enters a compound analogous to, and probably nearly isomorphous with, that of muscovite, except that it appears to contain more silica, and possibly a mixture of an orthosilicate, $\dot{R}_6Al_2(SiO_4)_3$ and a polysilicate, $\dot{R}_6Al_2(Si_3O_8)_3$, and contains considerable fluorine. It varies somewhat in composition in different occurrences, and in some cases may be represented as:

$$HKLiAl_3(SiO_4)_3 + K_3Li_3(AlF_2)_3Al(Si_3O_8)_3 \quad \text{lepidolite.}$$

It is to be noted that in this acid silicate the presence of lithium involves a higher silication than occurs in the analogous compounds with only potassium as the alkali metal, just as the normal lithium-aluminium silicate is higher than the common potassium one; compare the disilicate, petalite, with the polysilicate, orthoclase. All four of these mineral compounds may form beside one another in certain rock magmas. There is a strong analogy between the relationship just pointed out and the higher silication of the sodium-aluminium orthosilicate, nephelite, in proportion as potassium is present; potassium commonly forming higher normal aluminium silicates than sodium.

The mica most commonly formed in igneous rocks is biotite, which frequently accompanies muscovite, but oftener occurs without it. The biotite compound may be represented as follows:

$$(H,K)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3 \quad \text{biotite, in part,}$$
$$(H,K)_2(Fe,Mg)_2(Fe,Al)_2(SiO_4)_3 \quad \text{lepidomelane,}$$
$$[H,K,(MgF)]_3Mg_3Al(SiO_4)_3 \quad \text{phlogopite.}$$

These formulæ express different proportions among the constituent base-forming elements and the radical (MgF), there being gradations in the mixtures, as there are transitions between the various micas, some of which have distinctive names. Thus the compound with much iron, both ferrous and ferric, is lepidomelane; and the compound rich in magnesium, with very little iron and low aluminium, is phlogopite.

The orthosilicate, biotite, forms, like muscovite, in rock magmas by the side of polysilicates, metasilicates, or orthosilicates, and commonly with free silica, quartz. Like muscovite also its formation is not an invariable result of the cooling and crystallization of rock magmas. It is much less commonly produced in rocks solidified at, or near, the surface of the earth than in those crystallizing at some depths. Like muscovite it has not been produced in open crucibles in the laboratory. Its production is undoubtedly dependent on the greater chemical activity of hydrogen at high temperatures when under sufficient pressure; and all that has been said in connection with the formation of the muscovite compound in the presence of abundant silicon oxide may be applied to the production of biotite. In fact the latter may be looked upon chemically as a substitution derivative from muscovite by the introduction of Mg, $\ddot{\mathrm{F}}\mathrm{e}$ and $\dddot{\mathrm{F}}\mathrm{e}$. But it is understood, of course, that this does not involve the previous formation of muscovite followed by its transformation into biotite. The entry of magnesium and iron into the compound is because of their presence in the solution from which the mica formed. When they are present in very small amounts in the magma, muscovite forms; when they are both, magnesium and iron, present in nearly equal amounts, normal biotite forms; when the magma contains relatively much more iron than magnesium the mica is lepidomelane, when magnesium largely preponderates over iron, it is phlogopite.

The formation of biotite in magmas rich in silica, and in the presence of polysilicates, metasilicates, and free silica, indicates that hydrogen is able not only to bring about the lower silication of potassium-aluminium salts, but of magnesium-iron, for the acid orthosilicate, biotite, with abundant magnesium and iron, forms in magmas with magnesium-iron metasilicates,

pyroxenes, when there is sufficient silicon to convert the whole of the magnesium and iron into metasilicates. But, as these elements are not so active chemically as potassium, the reduction of magnesium and iron from metasilicates to orthosilicates is not so significant of the chemical activity of hydrogen under the conditions involved. It is significant, however, of the rôle which hydrogen probably plays in modifying the silication of magnesium and iron in rock magmas. For, as Tschermak has pointed out, the compound, biotite, may be looked upon as a mixture of molecules of muscovite with those of the orthosilicate, $(Mg,Fe)_2(SiO_4)$, when some of the aluminium is replaced by ferric iron. The magnesium-iron orthosilicate is the compound that crystallizes separately as olivine.

The formation of orthosilicate of magnesium and iron, olivine, in the presence of free silica, quartz, in rock magmas in which the metasilicate might be expected to form, is probably due to the hydrolyzing action of water at high temperature. That is, the chemical activity of hydrogen being greatly increased at high temperatures, the silicon, which might have combined with magnesium and iron to form a metasilicate, is divided between these elements and hydrogen so as to form orthosilicate of magnesium and iron and orthosilicate of hydrogen,

$$(Mg,Fe)_2(SiO_3)_2 + 2\ H_2O \rightleftarrows (Mg,Fe)_2(SiO_4) + H_4(SiO_4).$$

Should the magma solution containing these compounds become saturated with the magnesium-iron salt to such an extent through cooling that it is separated in a solid form, as olivine, the hydrogen orthosilicate might eventually split up into $H_2O$ and $SiO_2$ with the separation of silica in the solid form, as quartz, the water escaping subsequently from the magma.

**Leucite with Soda-Lime-Feldspars.** — It has been pointed out that leucite does not form in magmas with pure albite, though nephelite forms with orthoclase. And this has been used as an evidence of the stronger action of potassium toward silicon when compared with sodium and silicon. But leucite often forms by the side of soda-lime-feldspars, in which it is assumed that albite molecules and anorthite molecules are isomorphously crystallized. In such cases it is clear that sodium com-

bines with silicon in a polysilicate compound, while potassium forms a metasilicate. Some agency must be sought to bring about this reversal of the normal relation between potassium and sodium.

The formation of potassium-aluminium metasilicate with the sodium-aluminium polysilicate, or of the corresponding potassium polysilicate with the sodium aluminium orthosilicate, is in the nature of a reversible chemical action between substances in homogeneous mixture or solution. And the amount and character of the change taking place in a given time are known to depend upon the molecular concentration of each ingredient, as well as on intrinsic affinities, temperature, and solubility. The effect of molecular concentration of a substance in solution is sometimes erroneously called " mass action." By molecular concentration is meant the amount of molecules within a given volume. In general it may be said, when other things are constant, that the more molecules or atoms of anything that are in a given volume of liquid the greater chance for their encountering others and of making compounds with them.

There is still another factor capable of controlling the character of chemical action which shows itself in the act of crystallization of a compound from solution. It is the influence of one compound in a solid state to promote the crystallization of an isomorphous compound, or to induce the formation of one of several possible compounds from a saturated solution, and to form with it a solid solution. It is well known that a crystal of one kind of alum immersed in a saturated solution of another kind will cause the crystallization around itself of the alum in solution. It is also true that from a supersaturated solution, capable of producing hydrated salts of several degrees of hydration, a salt of any particular hydration, within certain limits, can be separated by introducing a crystal of the desired hydration. Applying these observations or laws to the problem in hand, it may be assumed that since anorthite forms isomorphous mixed crystals with albite, it may control the formation and crystallization of the polysilicate albite compound in a solution from which metasilicates and orthosilicates are capable of forming. And the extent to which this action takes place in solutions containing potassium-aluminium silicate

molecules will depend upon the molecular concentration of each, as well as on other factors. From this it should follow that the formation of albite with leucite should be greater the greater the molecular concentration, or the proportion of anorthite in the magma, other things being alike in the several cases compared.

**Pyroxenes. Mixed Salts.** — The metasilicates of calcium, magnesium, and iron, already mentioned, are mixed salts that may contain still other elements replacing the base-forming metals, besides other acid-forming elements than silicon, and may contain a subordinate amount of possibly an orthosilicate. The various compounds and mixtures crystallizing as pyroxenes may be represented as follows:

(1) $\ddot{R}(SiO_3)$, in which $\ddot{R}$ = Ca,Mg,Fe,[Mn].

(2) $\left\{ \begin{array}{l} \ddot{R}(SiO_3) \\ \text{with } \ddot{R}(\dddot{R}O)_2(SiO_4), \text{ in which } \ddot{R} = \text{Mg,Fe; and } \dddot{R} = \text{Al,Fe.} \end{array} \right.$

(3) $\dot{R}\dddot{R}(SiO_3)_2$, in which $\dot{R}$ = Na; $\dddot{R}$ = Fe,[Al]

(4) $(\dot{R}_2,\ddot{R})(\ddddot{R}O_3)$, in which $\dot{R}$ = Na,(ZrOF):
$\ddot{R}$ = Ca,Fe,[Mn]; $\ddddot{R}$ = Si,Zr,Ti.

The formation of these compounds is controlled in the first instance chemically by the proportions of the elements in solution and by the molecular concentration of each of the accompanying compounds. Their production is further controlled by physical relations affecting the stability of the several compounds at temperatures under which the magmas existed. The simplest compound of this group that forms in rock magmas is

$Mg(SiO_3)$ enstatite.[1]

It usually contains some Fe replacing Mg, and grades into hypersthene $(Mg,Fe)(SiO_3)$. These compounds form in magmas free from calcium, or in those in which calcium enters other compounds, oftenest feldspar. When there is calcium which may enter a pyroxene compound it commonly unites with equal amounts of (Mg,Fe), forming

$Ca(Mg,Fe)(SiO_3)_2$ diopside,

for it has been found that $CaSiO_3 \cdot MgSiO_3$ is a definite compound, which, however, is capable of taking up in solid solution about

[1] Allen, Wright, and Clement. Am. Jour. Sci., vol. 22, 1906, pp. 385–438.

60 per cent of $MgSiO_3$.[1] Still it frequently happens that these two kinds of compounds form by the side of one another, $Ca(Mg,Fe)(SiO_3)_2$ and $(Mg,Fe)(SiO_3)$, instead of an indefinite mixture of the two which would be $(Ca,(Mg,Fe))(SiO_3)$. But such intermediate compounds form in certain kinds of magmas, according to Wahl.[2]

Most frequently the pyroxene compound contains small and variable amounts of Al and $\dddot{Fe}$, its composition being represented by the expression

$$Ca(Mg,Fe)(SiO_3)_2 + Mg((Al,Fe)O)_2(SiO_4) \quad \text{augite.}$$

The entrance of aluminium into this compound with calcium, magnesium, and iron instead of entering anorthite feldspar compound with calcium alone, is probably due to molecular concentration and to the influence of the *common ion*, that is, to the relative proportions of possible diopside and anorthite molecules in the magma solution, and is in the nature of solid solution. But there are not sufficient data in hand to furnish more definite information. It is known that pyroxenes formed in the presence of lime-soda-feldspars differ in different rocks as regards the amount of aluminium contained in them. And in one igneous rock, from Ishawooa Canyon, Wyo.,[3] it is evident that about 19 per cent of anorthite molecules, which might have formed lime-soda-feldspar, has been incorporated in the abundant pyroxene compound. A similar effect of dominant magnesium molecules in controlling the disposition of a calcium-aluminium compound as a constituent of pyroxene instead of a feldspar has been noted by Pirsson.[4]

The metasilicate of sodium and ferric iron, $(Na\dddot{Fe}(SiO_3)_2$, acmite, forms in magmas in which there is insufficient aluminium to combine with all of the sodium to form polysilicate, albite, or orthosilicates, nephelite, or one of the sodalite group, and since it is isomorphous with other pyroxene compounds, it combines with them to a greater or less extent according to circumstances, forming transitions between diopside or augite and the pure compound, acmite. Its formation involves the presence of sufficient ferric iron, as well as a deficiency of aluminium. This acmite

[1] Allen, White, Wright, and Larsen. Am. Jour. Sci., vol. 28, 1909, pp. 1–47.
[2] Wahl, W. Die Enstatitaugite. Tscher. min. petr. Mitth., vol. 26, H. 1 and 2.
[3] Am. Jour. Sci., vol. 38, 1889, p. 46; and Jour. Geol. vol. 3, 1895, p. 938.
[4] 20th Ann. Rep. U. S. Geological Survey, pt. 3, p. 567.

compound should not be associated, then, with anorthite molecules, that is, with lime-soda-feldspars, or with strongly aluminous augite, unless molecular concentration, or the influence of the common ion, has been sufficient to control the formation of the calcium-aluminium compounds just mentioned and prevent the aluminium from uniting with sodium. This will undoubtedly be the case to some extent in certain rock mägmas. But the rule just enunciated is quite general in its application.

The highly complex compounds represented by the fourth formula, $(\overset{\mathrm{I}}{R}_2,\overset{\mathrm{II}}{R})(\overset{\mathrm{IV}}{R}O_3)$, are characterized by the presence of sodium, without aluminium or ferric iron, and by that of calcium without magnesium, and by a considerable content of zirconium, and in some cases titanium, which may replace silicon. There may also be fluorine and columbium. Such compounds crystallize as låvenite, rosenbuschite, and wöhlerite. They form in very small amounts in rock magmas rich in sodium, low in magnesium, and containing notable amounts of zirconium.

**Amphiboles. Mixed Salts.** — There are other metasilicate compounds closely analogous to the pyroxene compounds just mentioned, but differing from them in the relative proportions of the components, so far as concerns calcium especially, and also as regards the presence of notable amounts of hydrogen and fluorine in some cases; and crystallizing differently. These are the amphiboles, whose mode of formation and crystallization is discussed below. A general expression for their composition is similar to that of the pyroxenes, and according to Penfield may be

$\ddot{R}(SiO_3)$, in which $\ddot{R}$ = Mg, Fe, Ca, (Mn), $Na_2$, $H_2$, $(Al_2OF_2)$, $(Fe_2OF_2)$, $(Al_2O(OH)_2)$, $(Fe_2O(OH)_2)$.

The simplest amphibole compounds that correspond to enstatite, hypersthene, and diopside do not occur as primary minerals in igneous rocks. The amphibolic forms of $MgSiO_3$ have been produced pyrogenetically in the laboratory,[1] but are unstable, monotropic, crystal phases, which form at lower temperatures than the pyroxenic phases. For this reason they occur only as products of metamorphism that has taken place at temperatures lower than those of molten magmas. The com-

[1] Allen, Wright, and Clement. Am. Jour. Sci., vol. 22, 1906, pp. 385–438.

monest pyrogenetic amphibole, hornblende, is a complex metasilicate containing chiefly Mg, Fe, Ca, with Al, Fe, and Na in small amounts, but in larger proportions than in common augites. There are also present hydrogen, H, and generally fluorine, F. And the ratio between Ca and the other base-forming elements and radicals is approximately 1 : 3. Hornblende is less calcic than augite. The presence of hydrogen in the compound, though in smaller amount than in mica, indicates a similar origin for amphibole and mica compounds, namely, a hydrolytic one. Both kinds of compounds form under similar physical conditions, and commonly occur together in igneous rocks. It is probable that part of the hydrogen in hornblende is present as dissolved water in solid solution, since this has been shown to be the case with tremolite.[1]

The entry of aluminium into amphibole compounds instead of into feldspar molecules must be referred to molecular concentration and the influence of the common ion, for its formation clearly belongs to the category of reversible chemical actions, because it may, or may not, form in certain kinds of rock magmas according to attendant conditions.

The particular character of amphibole compound which forms in a rock magma depends primarily on the proportions of elements present, and secondarily on attendant conditions. Thus common hornblende with the composition mentioned above forms under favorable conditions in magmas of the average chemical composition and in others similar to them. In magmas richer in iron, amphiboles richer in iron commonly form, basaltic hornblende. In magmas rich in alkalies and aluminium, a distinctly sodic variety forms, arfvedsonite; in those with relatively less aluminium and sufficient iron, the sodium-iron-amphibole, riebeckite, is formed. The dependence of the formation of amphibole compounds upon attendant conditions is strikingly shown by the two igneous rocks from Gran, Norway, described by Brögger.[2] They have almost the same chemical composition, yet one crystallized into a mixture of hornblende and lime-soda-feldspar, while the other crystallized

[1] Allen and Clement. Am. Jour. Sci., vol. 26, 1908, pp. 101–118.

[2] Brögger, W. C. Erupt. Gest. Krist. Geb., vol. 3, 1899, p. 93; and Quart. Jour. Geol. Soc., vol. 50, 1894, p. 19.

almost completely into hornblende. The hornblende compound in the second case contains all the components of the feldspar and hornblende in the first mentioned rock.

The pyrogenetic amphibole compound that is commonly developed is a highly complex molecule whose formation may involve the constituents which might otherwise enter the following common pyrogenetic compounds:

$Ca(Mg,Fe)(SiO_3)_2$ ....diopside,
$(Mg,Fe)(SiO_3)$ ......hypersthene,
$CaAl_2(SiO_4)_2$.........anorthite,
$NaAl(Si_3O_8)$ .........albite,
$\ddot{Fe}\dddot{Fe}O_4$ ............magnetite,

besides H, F, Ti, and sometimes K from orthoclase. That its formation is due to conditions that may be attendant on physical factors, such as actual temperature, rate of change of temperature, or pressure, is shown by the frequency with which pyrogenetic hornblendes have undergone disintegration while in the molten magma, when the amphibole compound has split up into simpler compounds corresponding to those just mentioned. Such are the paramorphs of hornblende composed of monoclinic and orthorhombic pyroxene with magnetite, and sometimes with lime-soda-feldspar frequently met with in volcanic lavas, and most familiar to petrographers as black borders around hornblendes. Similar recomposition is shown by some micas, but not so frequently as with hornblendes. The highly complex molecule which is stable under some conditions falls to pieces readily under others. This should not be confused with the apparent relative stability of amphibole and pyroxene crystals under ordinary conditions near the earth's surface, when the amphibole appears to be the more stable solid. This introduces other properties of these crystals, and it is to be noted that the secondary amphiboles produced by metamorphism from pyroxenes are commonly the less complex compound, such as actinolite, which is not produced pyrogenetically. A corresponding pyrogenetic paramorphosis of pyroxene is seldom observed.

The formation of amphibole, like that of mica, considered as a chemical process, must be attributed to the action of hydrogen and other gaseous elements, like fluorine, within the magma at high temperatures. And since the resulting compound is

highly complex, the action may be considered to have been relatively rapid as compared with that permitting the formation of numerous kinds of simpler compounds, in which latter action the differences in the chemical activities of the various elements have opportunity to manifest themselves.

**Olivines. Mixed Salts.** — Orthosilicates of magnesium and iron,

$$(Mg,Fe)_2(SiO_4) \ldots \text{olivine},$$

are common pyrogenetic compounds, which are known to have formed from rock magmas together with metasilicates of the same metals, and with other metasilicates, orthosilicates and polysilicates, and in some instances with free silica, quartz. In most cases magnesium preponderates over iron in the compound, though there may be iron in the magma not silicated, indicating the stronger base-forming character of magnesium.

Calcium does not enter this pyrogenetic orthosilicate in notable amounts, although it is known to form with magnesium and iron the orthosilicate, monticellite, as a product of metamorphism. Calcium orthosilicate, $Ca_2SiO_4$, has been formed pyrogenetically in the laboratory,[1] in three enantiotropic, polymorphic, crystal phases, which are all unstable at low temperatures.

The proportions of magnesium and iron in olivines depends upon their relative proportions in the magma solution, though not necessarily directly. And it is to be expected that from magmas relatively rich in magnesium an olivine correspondingly rich in magnesium will form, and from those relatively poor in magnesium, if olivine forms, it will be correspondingly high in iron. Thus the almost pure iron metasilicate, fayalite, is known to form in certain highly alkalic rocks low in silica and almost free from magnesium.

The formation of the orthosilicate, olivine, instead of the metasilicate, hypersthene-enstatite, is commonly dependent on the amount of silicon in the magma available for combination with magnesium and iron, after the demands of the more active base-forming elements, potassium, sodium, and calcium, have been satisfied, as already stated in the earlier part of the discussion. But the repeated occurrence of olivine in rocks with

[1] Day, Shepherd, and Wright. Am. Jour. Sci., vol. 22, 1906, pp 265–302.

sufficient silicon to have formed metasilicate, hypersthene, and the frequent occurrence of olivine with pyrogenetic quartz in the same rock, also the concurrence of fayalite and quartz in lithophysæ in highly siliceous rocks, show that silicon may be deterred from forming the higher silicate under certain conditions, which appear to be, either those that permit the water present in rock magmas to enter into combination with the silica, forming a hydrogen silicate, $H_4SiO_4$, which, being stable only under the assumed conditions of temperature and pressure, subsequently breaks up into $H_2O$ and $SiO_2$ which may appear as quartz; or such that water may act catalytically to promote the immediate separation of silica in the form of quartz before the separation of the olivine compound from the solution.

Both kinds of action probably take place in different cases, or under different sets of conditions, and are illustrated by the formation of quartz and olivine in magmas like that at Cinder Cone, Cal., which contains enough available silicon to have converted all of the magnesium and iron into metasilicates. There are numerous instances in which olivine has formed in magmas which have sufficient silica to have raised the olivine compound to the metasilicate form, where the uncombined, or free, silica does not appear to be present as quartz, which, though undiscernible optically, must nevertheless exist in the groundmass of the rock, because of the chemical composition of the rock as a whole. This is the case of numerous basalts relatively high in silicon. Olivine is occasionally formed in rocks so rich in silicon that they are normally quartz-bearing, as in some dacites from Mount Shasta, Cal. On the other hand, quartz is sometimes formed pyrogenetically by the side of olivine in magmas so low in silicon that there is not sufficient to convert all of the magnesium and iron into metasilicates, as in some quartz-bearing basalts from New Mexico.

A special, and at the same time an extreme, instance of the chemical effect of water or its vapor at high temperature to reduce the silication of an iron silicate is furnished by hollow spherulites and lithophysæ in some highly siliceous igneous rocks, rhyolitic obsidians (p. 236). These pyrogenetic crystallizations contain abundant quartz and tridymite together with fayalite, which is orthosilicate of ferrous iron, or iron olivine, which has formed in the presence of much free silica from an extremely small amount of iron, less than one per cent. Within the body of the rock resulting from the same magma the iron has entered a metasilicate, pyroxene. The formation of the fayalite in the presence of abundant free silica is undoubtedly due to the action of the water vapor that was present in the cavities of the lithophysæ at the time of its crystallization from the magma.

**Garnets. Mixed Salts.** — Other orthosilicates that sometimes form in rock magmas have a composition represented by $\ddot{R}_3\dddot{R}_2(SiO_4)_3$, in which $\ddot{R}$ = Ca,

Mg, Fe, (Mn) and $\overset{\cdot\cdot\cdot}{R}$ = Al, Fe, (Cr, Ti) and in which Si may be partly replaced by Ti.

These are garnets which form a strictly isomorphous series of compounds with varying proportions among the constituent elements, certain mixtures having received specific names. The preponderant compounds in each case are given below.

. ......andradite (melanite).
$_4)_3$ ....schorlomite.
.......almandite.
........spessartite.
.......pyrope.
.......grossularite.

The compound $Ca(Mg,Fe)_2Al_2(SiO_4)_3$ corresponds to a mixture of anorthite, $CaAl_2(SiO_4)_2$, and olivine, $(Mg,Fe)_2(SiO_4)$. And in a sense garnet bears the same relation toward anorthite feldspar and olivine that biotite bears toward orthoclase feldspar and olivine. It is to be noted, however, that there is no hydrogen or alkali metal in garnet. The occurrence of the orthosilicate, garnet, together with mica in highly siliceous igneous rocks, with abundant free silica, quartz, and the difficulties attending the formation of garnets in open crucibles, suggest that in such rocks it owes its formation to a catalytic action of the water in the magma. It may be that such an agency is not required to bring about the formation of garnet in magmas low in silica, in which the production of orthosilicate is the normal chemical reaction. Moreover, in certain rocks of this kind garnet is more frequently formed.

The kind of garnet that forms in highly siliceous magmas is almandite, chiefly $Fe_3Al_2(SiO_4)_3$. That which forms in magmas rich in alkalies and low in silica is andradite, or melanite, chiefly $Ca_3Fe_2(SiO_4)_3$. In some of these magmas titanium enters the compound. The garnet sometimes formed in magmas rich in magnesium and low in silica is pyrope, chiefly $Mg_3Al_2(SiO_4)_3$. The formation of garnet in igneous magmas is not constant, and is more in the nature of an exceptional occurrence when all igneous rocks are taken into account. The formation of garnet compounds does not appear to be a chemical necessity following the molecular concentration of the components, but appears to result from special attendant conditions probably involving, as already said, a catalytic action of water in some instances.

**Epidotes. Mixed Salts.** — Somewhat more complex orthosilicate compounds, closely analogous to those of garnets and indicating the agency of water in their formation, occur still more sparingly pyrogenetically. They are:

$$\left.\begin{array}{l} Ca_2(AlOH)Al_2(SiO_4)_3 \\ Ca_2(FeOH)Fe_2(SiO_4)_3 \end{array}\right\} \text{.............epidote.}$$
$$(Ca,Fe)_2(AlOH)(Al,Ce,Fe)_2(SiO_4)_3 \text{.....allanite.}$$

Pyrogenetic epidote is formed occasionally in highly siliceous rock magmas, granites. And the cerium-epidote, allanite, is often formed in rock magmas with quite diverse compositions. It is always produced in very

small amounts, but its pyrogenetic nature is unquestionable. The action of the water in forming these compounds must have been that known as hydrolytic.

**Melilite. Mixed Salt.** — A basic silicate intermediate in composition between a metasilicate and an orthosilicate forms in certain magmas, which are not of very common occurrence. It is a silicate of calcium, with magnesium, iron, and aluminium in subordinate amounts, and owing to insufficient analysis is not clearly understood. Its composition may be represented as a mixture of the two compounds:

$$\text{Melilite} = \left[\begin{array}{ll} (Ca,Mg,Fe)_3((Al,Fe)O)_2(SiO_4)_2, & \text{gehlenite.} \\ \text{with } Ca_4Si_3O_{10} \ldots\ldots\ldots\ldots\ldots & \text{akermanite.} \end{array}\right.$$

Melilite forms directly from magmas of the proper composition without the intervention of a catalytic agent. It is distinctly a basic calcium silicate with low silica content, and with a small amount of aluminium when compared with the calcium-aluminium orthosilicate, anorthite. It forms in rock magmas rich in calcium, magnesium, and iron but poor in silicon and aluminium. It occurs in igneous rocks with little or no feldspar and very low silica. Attempts to produce akermanite in the laboratory from a simple mixture of its components have failed, and it seems probable that its production is only possible when other substances are present in the magma.[1]

**Zircon.** — Zirconium orthosilicate, $ZrSiO_4$, forms in rock magmas of various kinds even though the amount of zirconium is very small, and is not generally noted in the chemical analysis of the rock. It is commonest in the more alkalic rocks, with or without free silica. Zirconium is present in greatest amounts in alkalic rocks low in silica, and enters certain rare silicate compounds, probably replacing part of the silicon.

There are numerous uncommon silicate compounds, mostly complex salts, which are formed in particular magmas, chiefly those producing pegmatites, in which the presence, or the notable amount, of the less common, or rare, elements occasions exceptional compounds. Among those which are sometimes pyrogenetic may be mentioned tourmaline, containing boron; topaz, with fluorine; the zirconium-bearing minerals, eudialyte, catapleiite, låvenite, etc.; the glucinum minerals, beryl, leucophanite, etc.; minerals containing the cerium earths, besides many others, which may be found in Chapter II.

[1] Day, Shepherd, and Wright. Am. Jour..Sci., vol. 22, 1906, p. 280.

**Silicon Dioxide,** $SiO_2$, exists uncombined with base-forming metals, or as free silica, in many igneous rocks, and forms an independent compound which crystallizes as quartz, or tridymite, according to conditions attending the solidification of the magma. It oftenest forms in magmas having more silica than is required to form the silicate compounds commonly produced in rock magmas. Consequently it occurs, usually in the form of quartz, in rocks high in silica, and in those low in silica and with little alkalies, in which the less active base-forming elements are not sufficiently abundant to combine with all of the silica present. It may form in a rock with only 46 per cent of silica.

Free silica, or quartz, also exists in magmas in which water probably acts through hydrolysis, or as a catalyzing agent, and separates silica from compounds into which it has entered, or prevents such compounds from forming, as already noted in discussing the micas, amphiboles, and olivine.

**Titanium Compounds.** — Titanium, being quadrivalent like silicon and belonging to the same group of elements, has certain chemical resemblances to this element, and may replace it to variable extents in some silicates. Titanium is a weak, acid-forming element, and in some cases a weak, base-forming one. Though usually present in igneous rock magmas, it is generally in very small amounts.

As already said, it may enter silicate compounds in the acid radical, replacing silicon, and also it may enter as a weak metal. It is commonly present in small amounts in biotites, amphiboles, augites, and in some other silicates. It is a characteristic constituent of certain well-defined pyrogenetic compounds.

**Titanite and Perovskite.** — With silicon and calcium, titanium makes a definite compound, $CaTiSiO_5$, titanite, which forms in most rock magmas in which there is sufficient titanium and calcium. But it does not occur in magmas low in silicon, in which case a titanate of calcium without silicon is formed, $CaTiO_3$, perovskite. The same relationship between these compounds and the available silicon in the solution is shown in laboratory productions of these minerals.

**Ilmenite.** — Titanic acid combines with ferrous iron as $FeTiO_3$, ilmenite, and forms in various kinds of rock magmas in the pres-

ence of free silica, or silicic acid. The compound is most abundant in magmas richest in iron.

Titanium also enters iron ferrate, magnetite, and ferric oxide, hematite, in variable amounts. The extent to which this takes place in different compounds in rock magmas and the conditions controlling the distribution of titanium among the various compounds are not at present definitely known, so that no general relationships between the amount of titanium oxide in different pyrogenetic compounds and the amount in the magma can be stated.

**Rutile, $TiO_2$,** forms pyrogenetically to a slight extent in igneous rocks, and is found intimately associated with silica, quartz, the two oxides crystallizing together. It occurs in certain igneous rocks as minute inclusions in quartz crystals, indicating that the two chemically similar compounds had been closely associated in the liquid magma and had separated together, or at nearly the same time.

**Aluminium compounds** have been discussed in great part under the silicates, into which nearly all of the aluminium in rock magmas enters, except in certain extreme cases, namely: (1) when aluminium is in excess of all other base-forming elements with which it might combine to make the aluminous silicates already described; (2) when the silica is so low that these aluminous salts cannot be formed.

CORUNDUM, $Al_2O_3$. — In the first case mentioned aluminium oxide, $Al_2O_3$, remains uncombined and separates as corundum. It is to be noted that it does not combine with silica when this is available, as in the more siliceous magmas, to form aluminium silicate. This compound is common as a product of metamorphism, but rarely if ever forms pyrogenetically in rock magmas. Corundum occurs in igneous rocks with feldspars, chiefly without quartz, less often with it, and also with nephelite and muscovite. It sometimes occurs in rocks rich in magnesium and low in silicon, peridotites.

**Spinels. Mixed Salts.** — Aluminium may be weakly acid-forming and combine with magnesium and iron in the following pyrogenetic aluminates:

$(Mg,Fe)Al_2O_4$ ............ ceylonite or pleonaste.
$(Mg,Fe)(Al,Fe,Cr)_2O_4$ ..... picotite.

Such compounds are rarely developed in rock magmas, and then in very small amounts. The first compound, low in iron,

pleonaste, occasionally forms in the more siliceous rocks, the controlling conditions not being apparent. The second compound is more often formed, and then in magmas rich in magnesium and iron and low in silicon, peridotites, when there is magnesium in excess of the available silicic acid. In case there is only a small excess of magnesium and aluminium and a notable amount of chromium, the elements named enter chromite.

**Iron Compounds.** — Iron like aluminium when trivalent may form a weak acid, and as such partly replaces aluminium in the compounds just mentioned. It more commonly, and almost universally, in rock magmas forms an independent ferrous compound

$$\ddot{F}e\dddot{F}e_2O_4 \ldots\ldots\ldots \text{magnetite.}$$

This is chemically and crystallographically analogous to the spinels, and both elements enter isomorphously into spinels, but there are no transitional compounds formed in rock magmas. Titanium is frequently present in variable amounts. Iron ferrate forms in rock magmas of nearly all kinds of compositions where iron is present in appreciable amounts. Iron ferrate forms in rocks rich in silica and in the presence of uncombined silica, quartz. It is formed to a smaller extent in the more alkalic rocks, and is most abundant in the less siliceous rocks rich in iron and magnesium. But it forms in very different amounts in magmas of like chemical composition that have cooled under different conditions; thus it is more abundantly formed in basaltic lavas than in the chemically equivalent, coarse-grained gabbros.

That its formation, or its failure to form, is dependent on catalytic agents is shown by the fact that the hornblende compound may form and take up iron, both ferrous and ferric, which may subsequently be separated from it through paramorphism, when they appear as magnetite in a black border about the paramorphosed hornblende. It is also shown by the fact that fayalite is formed in lithophysæ through the action of heated water vapor and all the available iron compelled to enter a silicate compound. The oxidation of the iron may be changed also, one way or the other, or it may assume different valencies depending on other constituents of the magmas, especially water, and it may separate from solution as ferric oxide,

$$Fe_2O_3 \ldots\ldots\ldots \text{hematite.}$$

Hematite is often formed in small amounts in rock magmas, but never in such large amounts as the corresponding aluminium oxide, $Al_2O_3$, corundum. Owing to its resemblance to magnetite when in minute crystals in igneous rocks hematite is often mistaken for magnetite. It appears to be formed commonly in small amounts in the more alkalic igneous rocks, both the more siliceous and less siliceous kinds.

The stronger base-forming elements common in igneous rocks have all been discussed in connection with the salts into which they enter and need no further treatment in this place. Compounds formed by the minor or rarer elements occurring in igneous magmas will not be considered in this general discussion, but may be noticed in special cases elsewhere.

**Mineral Compounds in the Average Magma.** — Having considered the possible chemical compounds that may form in rock magmas under the ordinary circumstances attending the formation of igneous rocks, it will be instructive to discuss the mineral compounds that may form in a rock magma having the composition of the average analysis. The calculation of the proportions of pyrogenetic minerals is shown in the accompanying table. Starting with the relative number of atoms of the various elements in the average analysis in the first column, the apportionment of them to the several compounds is shown in succeeding columns. The method of procedure is the following: Apatite is first disposed of because phosphorus appears to enter this compound wholly. Orthoclase is reckoned on a basis of the potassium, as this is the strongest base-forming element, there is abundant silicon, and it may be assumed at first that no aluminous ferromagnesian compounds are formed; that is, no biotite, or hornblende, or augite. Such a condition is often nearly realized in some volcanic lavas having this chemical composition. Albite is next set aside on the basis of the sodium present, as this element is next to potassium in activity. With the remaining aluminium anorthite is calculated, as calcium is the next element in the electromotive series. There remain a certain amount of calcium and a larger amount of magnesium and iron, besides ferric iron, titanium, silicon, etc. The titanium may form titanite, or ilmenite, or both; the ferric iron may form magnetite; not knowing any relation between the possible titanite and

| | 2.943 O | .003 P | .994 Si | .009 Ti | .294 Al | .032 $\dddot{F}e$ | .047 Fe | .101 Mg | .085 Ca | .109 Na | .062 K | .168 H | F etc. | Atomic proportions in analysis of average rock. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (CaF) $Ca_4(PO_4)_3$ | 12 | 3 | | | | | | | 5 | | | | 1 | Apatite | .50 | |
| $KAlSi_3O_8$ | 496 | | 186 | | 62 | | | | | | 62 | | | Orthoclase | 17.24 | |
| $NaAlSi_3O_8$ | 872 | | 327 | | 109 | | | | | 109 | | | | Albite | 28.56 | |
| $CaAl_2(SiO_4)_2$ | 492 | | 123 | | 123 | | | | 62 | | | | | Anorthite | 17.24 | |
| $CaTiSiO_5$ | 45 | | 9 | 9 | | | | | 9 | | | | | Titanite | 1.76 | 33.18 |
| $\ddot{F}e\dddot{F}e_2O_4$ | 64 | | | | | 32 | 16 | | | | | | | Magnetite | 3.71 | |
| $Ca(Mg,Fe)(SiO_3)_2$ | 54 | | 18 | | | | 2 | 7 | 9 | | | | | Diopside | 2.00 | |
| $(Mg,Fe)(SiO_3)$ | 369 | | 123 | | | | 29 | 94 | | | | | | Hypersthene | 13.23 | |
| $SiO_2$ | 416 | | 208 | | | | | | | | | | | Quartz | 12.48 | |
| $H_2O$ | 84 | | | | | | | | | | | 168 | | Water | 1.51 | |
| Extra O | 39 | | | | | | | | | | | | | | .62 | |
| Etc. | | | | | | | | | | | | | | | .64 | |
| | | | | | | | | | | | | | | Total | 99.49 | |
| $FeTiO_3$ | 27 | | | 9 | | | 9 | | | | | | | Ilmenite | 1.37 | 33.20 |
| $\ddot{F}e\dddot{F}e_2O_4$ | 64 | | | | | 32 | 16 | | | | | | | Magnetite | 3.71 | |
| $Ca(Mg,Fe)(SiO_3)_2$ | 108 | | 36 | | | | 3 | 15 | 18 | | | | | Diopside | 3.99 | |
| $(Mg,Fe)(SiO_3)$ | 315 | | 105 | | | | 19 | 86 | | | | | | Hypersthene | 11.11 | |
| $SiO_2$ | 434 | | 217 | | | | | | | | | | | Quartz | 13.20 | |

ilmenite, it may be better to calculate first one and afterwards the other, and show the difference in the other compounds resulting from each assumption. When titanite is reckoned, the magnetite may be calculated as in the next column. With the remaining calcium, 9 atoms, diopside may be calculated by introducing magnesium and ferrous iron in approximately the proportions they bear to one another in the magma after the iron is set aside for magnetite. The remaining magnesium and iron may be allotted to a metasilicate, hypersthene, because of the abundance of silicon in the magma. The remaining silicon is reckoned as quartz. There remain hydrogen as water, and an excess of oxygen belonging to the elements not taken into account, amounting together to 1.26 per cent of the whole. The percentage weights of the several mineral compounds are given in their proper place, and the sum shows a loss of about half a per cent through imperfect methods of calculation. A recalculation is shown of those compounds following the feldspars when all the titanium is allotted to ilmenite.

The mineral composition corresponds to that of many volcanic lavas so far as mineral molecules are concerned. The apparent mineral composition of the rock may be somewhat different owing to the non-appearance of microscopic crystals of orthoclase and quartz, but the full significance of this discrepancy will be explained in a subsequent chapter.

Having calculated a possible mineral composition for the rock without any aluminous ferromagnesian compounds, the question arises how far this may be in error, and what would result from the introduction of aluminous pyroxene, hornblende, and biotite. As to the development of aluminous pyroxene — augite — instead of diopside, the data are insufficient to warrant a definite statement at this time. Diopside with less than 1 per cent of alumina is known to form in rocks of nearly this composition, as well as in much less siliceous and more pyroxenic magmas. So this assumption may not be appreciably in error. As to hornblende and biotite, they may not be developed at all, or may form to the complete absorption of all of the magnesium and iron in the magma, with possibly a little iron oxide, or ilmenite. In order to recalculate the analysis so as to produce both hornblende and biotite, it is necessary to consider the possible compo-

sition of each of these mixed salts, whose elemental proportions will depend on the proportions of the characteristic elements in the magma solution. A study of analyses of hornblendes and biotites in igneous rocks, somewhat similar in chemical composition to the average analysis, shows the two following analyses to be probable approximations to the composition of hornblende and mica that may be expected to form in the average magma.

| | I | Ia | II | IIa |
|---|---|---|---|---|
| $SiO_2$ | 45.76 | .762 | 35.79 | .596 |
| $Al_2O_3$ | 8.80 | .086 | 13.70 | .134 |
| $Fe_2O_3$ | 5.32 | .033 | 5.22 | .032 |
| FeO | 11.23 | .156 | 13.72 | .190 |
| MgO | 14.08 | .352 | 12.13 | .303 |
| CaO | 10.62 | .189 | .05 | .001 |
| $Na_2O$ | 1.39 | .022 | .15 | .002 |
| $K_2O$ | .26 | .003 | 9.09 | .097 |
| $H_2O$ | .85 | .... | 4.85 | .... |
| $TiO_2$ | 1.43 | .018 | 3.51 | .044 |
| MnO | .57 | .008 | .19 | .002 |
| | | .... | F .76 | .032 |
| | 100.31 | .... | etc. .43 | |
| | | | 99.59 | |

I. Green hornblende from dacite, Grenatilla.

Ia. Molecular ratios.

II. Biotite from quartz-monzonite, Butte, Mont.

IIa. Molecular ratios.

In order to readjust the compounds to accommodate these complex salts the following considerations are necessary: Forming hornblende reacts on anorthite for aluminium and on albite for sodium, neglecting the very small amount of potassium in the hornblende analysis. Forming biotite reacts on orthoclase for potassium and on anorthite for the extra aluminium in excess of the potassium in biotite. The limit to the amount of these elements that may be transferred from feldspar compounds to hornblende and biotite of the compositions given is fixed by the total amount of magnesium and iron in the magma, if the maximum amounts of these minerals are to be formed. The problem may be solved approximately by algebraical methods thus:

$$\begin{aligned} Ca_h &= Ca_d + Ca_{an_h} + Ca_{an_b}, \\ Al_h &= Al_{an_h} + Al_{ab} \quad \text{and} \quad Ca_{an_h} = \tfrac{1}{2} Al_{an_h}, \\ Na_h &= Al_{ab}, \end{aligned}$$

where $Ca_h$ is the calcium in the hornblende; $Ca_d$, that in the calculated diopside; $Ca_{an_h}$, that derived from anorthite for hornblende; $Ca_{an_b}$, that derived from anorthite for the excess Al in biotite. $Al_h$ is the aluminium in the hornblende; $Al_{an_h}$, that derived from anorthite transferred to hornblende; and $Al_{ab}$, that from the albite transferred. $Na_h$ is the sodium in the hornblende. Similarly

$$\begin{aligned} K_b &= Al_{or}, \\ Al_b &= Al_{or} + Al_{an_b}, \quad \text{and} \quad Ca_{an_b} = \tfrac{1}{2} Al_{an_b}, \end{aligned}$$

where $K_b$ is the potassium in the biotite; $Al_{or}$, the aluminium derived from orthoclase; $Al_{an_b}$, the aluminium derived from anorthite for the excess in biotite; $Al_b$, the aluminium in biotite.

From the molecular ratios in the analyses the atomic ratios of each of the elements with calcium or potassium may be found, from which the following may be used:

$$\text{In hornblende: } \frac{(Mg,Fe)_h}{Ca_h} = 2.69.$$

$$\frac{Al_h}{Ca_h} = 0.91, \quad \frac{Na_h}{Ca_h} = 0.26.$$

$$\text{In biotite: } \frac{(Mg,Fe)_b}{K_b} = 2.46, \quad \frac{Al_b}{K_b} = 1.34.$$

Total $(Mg,Fe) = (Mg,Fe)_h + (Mg,Fe)_b = 148$, assuming that all the titanium enters hornblende and biotite. The calcium in the estimated diopside is $Ca_d = 18$. Solving the equations there result

$$(Mg,Fe)_b = 69, \quad (Mg,Fe)_h = 79 \quad \text{and}$$
$$Ca_h = 29, \quad K_b = 28.$$

From these the percentages of hornblende and biotite may be estimated approximately from the analyses of each mineral, yielding 15.39 per cent hornblende and 14.38 per cent biotite.

Readjusting the feldspars and magnetite for the loss, the mineral proportions become:

| | | | |
|---|---|---|---|
| Apatite | 0.50 | Apatite | 0.50 |
| Orthoclase | 9.46 | Orthoclase | 17.24 |
| Albite | 24.63 | Albite | 28.56 |
| Anorthite | 14.18 | Anorthite | 17.24 |
| Hematite | 1.12 | Ilmenite | 1.37 |
| Hornblende | 15.39 | Magnetite | 3.71 |
| Biotite | 14.38 | Diopside | 3.99 |
| Quartz | 18.29 | Hypersthene | 11.11 |
| Water | .84 | Quartz | 13.02 |
| etc | 1.26 | Water | 1.51 |
| | | etc | 1.26 |
| | 100.05 | | 99.49 |

The mineral composition is that of a quartz-mica-diorite, with 38 per cent of andesine feldspar and nearly 10 per cent of orthoclase. A comparison of the pyroxene-andesite with the chemically equivalent diorite shows that with the complete development of hornblende and biotite the orthoclase molecules have decreased to almost one-half; the lime-soda-feldspar has decreased about one-seventh, the two molecules, albite and anorthite, about equally; quartz has increased almost one-half; the iron "ores"

have decreased about four-fifths, and the ferromagnesian silicates have almost doubled in amount. It is to be noted that the production of mica and hornblende is accompanied by a liberation of silicon from silicates to produce an increase in quartz, corresponding to the reactions discussed on pages 133 and 140, and referred to possible hydrolysis, or a catalytic action of the water in the magma.

# CHAPTER V

## SEPARATION OF SUBSTANCES FROM SOLUTION

HAVING considered the possible chemical reactions that may give rise to mineral compounds in rock magma, it is in order to discuss the process and results of separation of various compounds or substances from magma solutions upon the change of physical conditions attending the eruption of such magmas and their solidification into rocks. The changes in physical conditions are those of temperature through cooling and of pressure through eruption or other movements. The compounds or substances that may separate from a magma solution are in part gases, to a less extent, probably, liquids, but in most part solids. They will be discussed in the order given.

**Separation of gases.** — That gases escape from rock magmas in large volumes at the time of their eruption as volcanic lavas is well known. The great bulk of these gases is the compound $H_2O$, possibly .999 of the whole volume of gas given off at a volcanic eruption. Other gases, which appear to vary in their abundance in different volcanic centers and at different eruptions, and also at different periods of volcanic activity at what may be considered one eruption, are: hydrogen, H, to some extent, and oxygen, O; hydrogen chloride, HCl; hydrogen sulphide, $H_2S$; besides sulphurous acid, $H_2SO_3$, and sulphuric acid, $H_2SO_4$; fluorine, F, and boron, B, also other gases in small amounts, such as marsh gas, $CH_4$, carbon dioxide, $CO_2$, and nitrogen, N. The occurrence of these latter gases is such that in great part they appear to accompany volcanic eruptions as the result of contact metamorphism, that is, as products of alteration produced directly or indirectly by the magma on neighboring substances, rather than to proceed from direct separation from the magma itself.

It is known also that gases escaping from volcanic lavas through vents or crevices, deposit, to a slight extent in such cases, compounds containing silica and base-forming elements; in fact, silicates similar to those separating in solid form within the magma, feldspars, pyroxenes, etc., as well as iron oxide and other oxides. These were probably dissolved in the escaping

**gases, chiefly $H_2O$, and under such conditions must be considered to have escaped in a gaseous condition. They show that magma vapors exist at high temperatures, which corresponds to the occurrence of vapors of other liquids and liquid solutions. The higher the temperature, other things being alike, the greater the vapor tension, the more of these compounds capable of escaping as vapor. The bearing of this on contact metamorphism is apparent.**

The separation of gas from a magma solution affects the chemical composition and the physical character of the liquid. Chemically it reduces the molecular concentration of the substances that have escaped, and must, so far as these substances are active chemically, change the chemical equilibrium existing before their escape. The result of this change may show itself, or not, in the solidified rock, according as it has affected noticeably the stability of solid compounds that may have previously separated, crystallized, from the solution, or as it may influence the subsequent character of solids crystallizing, or of the complete solidification of the whole magma. Physically the separation of gas from rock magmas affects their liquidity, or viscosity, that is, their molecular mobility. It must also affect the temperature of the mass by lowering it. These physical changes will modify the separation of solid compounds, chiefly their crystallization, which will be considered at length in the next chapter.

The separation of gas from rock magma, while taking place most freely and copiously at the surface of the earth, when the magma is in the upper part of the crater of a volcano, and on the surface as a lava flow, also takes place through surrounding rocks according to their permeability and to the possible back pressure of vapors, or liquids, already present in them.

Gas may separate from a liquid in consequence of the change in composition, or volume, of the liquid, due to the crystallization of solid compounds from it, whereby the remaining liquid may become overcharged with the gas for existing temperature and pressure.

**Separation of liquids** from a liquid solution takes place when upon a change of physical conditions or of chemical composition the liquids are no longer miscible in the proportions in which they may have been mutually dissolved previous to the changes mentioned. Whether liquid silicate compounds are miscible in all proportions at all temperatures and pressures under which rock magmas exist is not definitely known. It is of course understood

that cases in which chemical reactions take place are excluded from this statement. They may, or may not, be accompanied by separation of solid compounds. It appears as though the liquid compounds corresponding to the silicates crystallized from rock magmas are miscible in one another in all proportions.

It has been suggested, however, by some petrographers[1] that they may not be miscible in all proportions, and that at lower temperatures there may be a separation of a rock magma into different silicate liquids prior to crystallization. But of this there appears to be no direct evidence within the solidified magmas, igneous rocks.

That liquid silicates and liquid sulphides are not miscible in all proportions has been demonstrated by Vogt[2] in his studies on furnace slags. He has shown that monosulphides of the metals, Ca, Mn, Fe, Zn, (Mg), etc., are soluble in silicate slags to a limited extent, being more soluble in those richer in calcium and manganese. The solubility increases greatly with rise of temperature, and it appears that at high temperatures, under great pressure, rock magmas low in silica and rich in calcium, magnesium, and iron, gabbros, containing $H_2O$, and possibly other gases, are miscible in all proportions with sulphides of iron, since transitions are known between such rocks and those containing varying amounts of sulphides up to 100 per cent. The more magnesian igneous rocks, peridotites, like the more magnesian slags, carry less sulphides than the more calcic rocks may contain.

It is probably incorrect to think of $H_2O$ separating as a liquid from liquid rock magmas. At the temperature at which rock magmas are liquid $H_2O$ separated from them would be a gas above its critical temperature, 358° C. Upon loss of heat it would become water.

## SEPARATION OF SOLIDS FROM SOLUTION

The separation of solids from solution depends upon the attainment of a sufficient molecular concentration of the substance, or substances, to saturate the solution. This concentration may be brought about in one of several ways: (1) by chemical reaction within the solution consequent upon the addition of substance from without; (2) by loss of a substance that may be necessary to maintain the chemical equilibrium of the solution; (3) by change of temperature, in most cases by lowering temperature; (4) by change of pressure, either (*a*) acting directly to affect saturation, in any particular case operating in the opposite manner to change of temperature, that is, generally an increase of pres-

[1] Bäckström, H. Jour. Geol., vol. 1, 1893, pp. 773–779.
[2] Vogt, J. H. L. Die Silikatschmelzlösungen, I, Christiania, 1903, pp. 96–101.

sure promoting saturation; or (*b*) acting indirectly through change of chemical equilibrium, or by permitting the escape or accession of gases. Each of these possibilities will be considered separately as to their probable occurrence in rock magmas, the general results of separation by any of these means being discussed for all together.

(1) The *addition* of *substances* to a rock magma while it is still liquid and uncrystallized may result from an accession of gas from adjacent rock masses during eruption, or after it has been intruded within solid rocks. As the greater part of such gas may be $H_2O$, and as the general effect of the accession of gases must be to reduce molecular concentration of other compounds soluble in rock magmas, it may be assumed that the effect of the accession of gas would be to reduce saturation. It is possible, however, that hydrolysis of certain silicates may ensue, which might result in the production of less soluble compounds that might supersaturate the magma and separate as solids, crystals.

In case a magma were superheated to such an extent that it could melt adjacent solid rock without itself cooling below the solidifying point, there might be a mixture of material of such a kind that the accession of substances furnishing ions like some in the intruded magma might bring about supersaturation with respect to a compound containing these ions, and so produce separation of solids. But there are few indications that such accessions to rock magmas have taken place in notable amounts. Indeed most evidence is to the effect that molten magmas are not sufficiently superheated at the time of their intrusion into rocks, subsequently exposed at the earth's surface, to permit them to melt any considerable amount of the solid rock with which they may have come in contact.

(2) The *loss* of *substances*, which may be necessary to maintain the chemical equilibrium of solution, whereby a separation of solids from the solution may take place is most likely to happen through the escape of gas, chiefly $H_2O$. Since, as just stated, the presence of gas in general reduces the concentration of other compounds soluble in rock magmas, its escape from the magma must increase the concentration and thus promote the separation of solids from solution when the molecular concentration is sufficiently near the point of saturation. The effect is the same as that produced by the evaporation of the solvent in an aqueous solution.

(3) The *lowering* of the *temperature* of most solutions, and

certainly of rock magmas, increases molecular concentration and brings about saturation of the compounds in solution. As this is the chief cause of the separation of solids from rock magmas which cool down from high temperatures to the ordinary temperature of the atmosphere, the process will be discussed at length after a brief consideration of the effects of changes of pressure.

(4) *Changes* of *pressure* act in the opposite direction to corresponding changes of temperature in most cases, and especially in the case of rock magmas. But the degree of effect produced is markedly different in the two operations. Barus has shown that in the case of molten basalt a rise of temperature of one degree is counteracted by a pressure of forty atmospheres,[1] and evidences are manifold that the general effect of pressure is relatively small as compared with that of temperature.[2] But it is to be noted that in the process of magma eruption changes of pressure may act much more quickly than those of temperature, since one is transmitted instantaneously through a mass and the other by the slow process of diffusion. The changes of pressure experienced by rock magmas during eruption must be almost universally those of decreasing pressure. It is conceivable that conditions of increasing pressure may in some cases obtain, though rarely. Changes of pressure affect the solubility of gases in rock magmas, diminished pressure permitting their partial escape and bringing about conditions discussed under (2).

Since changes of temperature are the most potent causes of changes of saturation in solutions, and since the effects of pressure changes are similar but in the opposite direction and are much less, the general discussion of the subject of saturation of rock magmas and the separation of solids from them may proceed along the lines of the better known relationships between temperature and saturation.

**Saturation and Supersaturation.** — In rock magmas loss of heat increases molecular concentration and, when the temperature has reached a certain point in a particular solution under a given pressure, saturation with respect to a particular compound is attained. But, as is well known, it does not necessarily follow

[1] Barus, C. U. S. Geological Survey, Bulletin 103, 1893.

[2] Iddings, J. P. Phil. Soc. Washington, Bulletin, vol. 11, 1889, pp. 106–108.

that the separation of molecules of this compound in solid form will take place the moment the temperature passes below the temperature of saturation. It may reach a considerably lower point, or be maintained for long periods somewhat below the saturation point, without separation taking place, the solution becoming supersaturated. As already stated, Chapter III, the ability of a compound to supersaturate a solution varies with the compound and the solution, and is somewhat greater when there is a chemical similarity between the two. It should, therefore, be relatively great when the two have the same composition, that is, when a single compound is passing from a liquid to a solid state. It depends also upon the physical character of the liquid whether it is more or less liquid or viscous at the temperature of saturation, the more viscous liquids becoming more readily supersaturated. This is illustrated by the greater frequency with which the more viscous, highly siliceous, lavas — rhyolites — solidify without the separation of crystallized compounds, when compared with the more liquid basaltic lavas.

**Metastable Condition.** — From supersaturated solutions separation of solids may be started by introducing in them a solid of the compound with which the solution is saturated. In laboratory experiments it has been found that minute, even imperceptible particles of such compounds may be introduced from the atmosphere of the laboratory, and it is necessary to prevent contact of the solution and the uncleansed atmosphere in order to maintain supersaturation, and it has been found that, when all chance of admission of such solid substances, sometimes called crystallizing "germs," has been cut off by keeping the solution in a closed vessel, it is possible in some cases to maintain some solutions in a supersaturated condition indefinitely. This condition of a solution is known as a METASTABLE [1] one. It is one in which there is a suspended transformation of a substance from a liquid to a solid phase; one in which the presence of the solid phase is often necessary to bring about the transformation.

Besides contact with the proper solid it is known that agitation promotes separation of solids from solution, and that quiet aids supersaturation. It may be expected, then, that rock mag-

[1] Ostwald, W., Zeitschr. phys. Chem., vol. 22, 1897, p. 302; and Miers, H. A., Trans. Chem. Soc., vol. 89, 1906, p. 427.

mas would tend toward greater supersaturation the quieter they remain during cooling. Intruded lavas may be assumed to be quieter than lavas in the conduit of a volcano. The question suggests itself, To what extent will an earthquake shock disturb the equilibrium in a metastable intruded rock magma?[1] Any effect must be dependent on the degree of supersaturation and the character of the earthquake. In many cases liquid magmas are in contact with the solid phase of particular compounds when these exist as minerals in the adjacent rocks, so that supersaturation at the immediate margin of the magma body in such cases is unlikely.

**Labile Condition.** — When the temperature of any solution reaches a sufficiently low point separation of solid takes place, whether there is contact with solid phase or not. This is called the LABILE[2] condition of the solution. A distinction between a metastable and a labile condition of solutions is in some cases well defined, in others not at all definite. In laboratory experiments the arrival of the labile condition of a solution is indicated by a shower of solid particles, when previous separation had been going on more gradually at scattered points.

Very interesting accounts of the two processes of separation in certain solutions are contained in papers by Miers[3] and his assistants. They are full of suggestions of possible application to the problem of the crystallization of igneous rocks, and will be referred to again in connection with the texture of these rocks.

**Number of Points of Separation.** — The transition of liquid to solid phase takes place at points as noted by Gibbs, and in general it may be said that separation from solutions in the metastable condition of supersaturation takes place at relatively few points, while in the labile condition it happens at very many. This has to do with the *relative numbers of points of separation* in a given

[1] The same question has been raised by W. O. Crosby in connection with the possible origin of porphyritic texture. Am. Geol., vol. 25, 1900, p. 307.

[2] Ostwald, W., Zeitschr. phys. Chem., vol 22, 1897, p. 302; and Miers, H. A., Trans. Chem. Soc., vol. 98, 1906, pp. 427.

[3] Miers, H. A., and Isaac, Florence. Jour. Chem. Soc., vol. 89, 1906, p. 413; Rep. Brit. Assoc. for 1906, p. 522; and Proc. Roy. Soc., 1907.

Miers, H. A., and Chevalier, J. Min. Mag., vol. 14, 1906, p. 123.

Barker, T. V. Jour. Chem. Soc., vol. 89, 1906, p. 1120, and Min. Mag., vol. 14, 1907, p. 235.

Chevalier, J. Min. Mag., vol. 14, 1906, p. 134.

volume of solution, the greatest number occurring in the labile condition, a smaller number in the metastable. Consequently the fewest should be expected to occur when the solution is in a condition of relatively slight supersaturation, when it has just passed the point of saturation.

The number of points, or nuclei, of separation developed in a unit of liquid in a unit of time for a given temperature has been taken by Tammann[1] as a measure of spontaneity of crystallization.

In a system of equilibrium between liquid and solid phases with constantly varying temperature, such as that under discussion, there must be corresponding shifting of the degree of saturation in the solution. This is the case of eruptive rock magmas. If separation begins soon after the point of saturation is reached, it should occur at a few points scattered through the liquid. The separation of solid substance reduces the degree of supersaturation, which would return to the saturation point if the temperature remained constant. When, however, the temperature is falling at a more rapid rate than that at which the separation is able to reduce supersaturation, higher degrees of supersaturation of the solution are attained. In these separation may take place from a greater number of centers, while it is still proceeding at those centers already established in the solution. And if the labile condition is reached before all the substance in question has been separated, it will be separated as it were in a shower from a much greater number of points than previously. The bearing of this set of conditions on the crystallization and texture of rocks is discussed in Chapter VI.

**The Rate of Separation** of a substance from solution may be defined as the amount of substance that separates in a unit of time, taken by itself, or as compared with the total amount of the substance in solution. In the second case the rate of separation is clearly a function of the total amount in solution, that is, of the *molecular concentration of the substance*. In the first case, also, the rate of separation is dependent on the molecular concentration. For, other things being alike, the absolute amount of a substance separating from a solution in a unit of time will be greater the greater the total amount in solution. The same

[1] Tammann, G. Kristallisieren und Schmelzen, Leipzig, 1904, p. 149.

relationship may be expressed in another manner, as follows: The rate of separation will vary as the *solubility* of the substance, for if a given amount of substance is dissolved in a unit of time through rise in temperature, the same amount should be separated in the same time through a corresponding fall in temperature, if supersaturation does not intervene. The greater the solubility the more is dissolved. This law has been stated more definitely in somewhat different form as follows: the velocity of crystallization (separation in solid phase form) is diminished by the addition of foreign substances to the liquid phase of a substance, the diminution of the velocity being the same for equimolecular quantities of all substances.[1]

When supersaturation exists the molecular concentration is greater than at the point of saturation, consequently the higher the degree of supersaturation at which separation takes place the greater the rate of separation for a particular case. The highest rate, then, is attained when separation takes place in the labile condition. This maximum rate of separation has a definite characteristic value for each substance in a given solution, and remains constant over a certain range of temperature change. After this, at lower temperatures, the rate diminishes somewhat rapidly, and with sufficient supercooling may become zero, on account of increased viscosity, when the solution passes into a glass.[2]

Since solubility increases at a greater rate than temperature increases, that is, the additional amount dissolved for an increase of one degree of temperature is greater the higher the temperature, so the amount separated for a fall of one degree will be greater the higher the temperature at which saturation is reached, the rate of change of temperature being constant.

Evidently the rate of separation depends on the rate of *change of temperature*, other things being equal, for the faster the temperature falls in a unit of time the more substance separates, provided other factors, such as viscosity, do not intervene to prevent separation altogether. It is to be noted that when the temperature changes at a uniform rate, the rate of separation, if it follows closely the attainment of saturation, should be greater

[1] Von Pickardt, Zeitschr. phys. Chem., vol. 42, 1902, p. 17; also Findlay, Alex., The Phase Rule, 1904, p. 71.

[2] Findlay, *ibid*, p. 70.

at higher temperatures than at lower. When, however, temperature changes at a variable rate, the rate of separation should be variable and in a similar degree. Rock magmas must change temperature at very different rates according to experiences of eruption which will be discussed at length in connection with differentiation in Chapter VII.

**The Effect of Viscosity on the Rate of Separation.** — The rate of separation is a function of viscosity, that is, it varies with the viscosity or liquidity of the solution. This is shown by the fact that while heat is being lost at a rapid rate some solutions become so viscous that they pass into a solid state as a whole, without any separation of dissolved substances taking place. They become amorphous glasses, or homogeneous mixtures, which are in fact rigid solutions, from which by extremely slow processes the same compounds may in some cases separate that would have separated in short times from the solutions when liquid. This calls attention to the distinction between the character of the solids separating from solutions and that of a rigid solution such as amorphous glass. The former are always crystallized, and though no substances are known to separate from a solution, rock magma, in an uncrystallized, amorphous, condition the solidification of an isolated substance does not always involve crystallization. For liquid feldspar, by itself, may be cooled so rapidly as to pass into amorphous glass without any part of the liquid crystallizing, though the molecular concentration is complete and the transition temperature has been passed during cooling. Many compounds may be chilled to glass in a similar manner, but a comparison of their behaviors shows that the rate of cooling necessary to produce the amorphous condition varies with the fluidity of the liquid compound as it approaches the crystallizing temperature; the more fluid the liquid the more rapid must be the rate of cooling necessary to prevent crystallization, some liquids being so fluid that they have never been reduced to an amorphous solid condition, but always crystallize. This is the well-known case with water. The more viscous the liquid the more readily it may be cooled as a glass, and some liquids, like melted albite feldspar, or melted silica, are so extremely viscous as they approach the solidifying point that they have never been obtained in crystals in the laboratory by the cooling of the pure liquids.

It appears from these considerations that high viscosity may affect both the crystallizing of a substance from a pure liquid of the same composition, and also in other cases when the substance supersaturates a solution or mixture of substances. In the first case the molecules in contact with one another do not have time to arrange or orient themselves into the arrangements which constitute crystals. The action which was prevented was one of turning or orientation. When a compound that saturates a solution is present in comparatively small amount it is evident that its molecules, uniformly distributed throughout the liquid, must diffuse through the liquid, that is, pass among the molecules of other, more abundant compounds, in order to gather together to form crystals. The diffusion is prevented by high viscosity, and the whole solution becomes homogeneous glass, for in it the molecules of the various compounds are uniformly mingled. The two cases are thus distinguished from each other. Since the act of separation of a solid from a solution involves the diffusion of its molecules and this requires time, and is affected by the molecular mobility, fluidity, of the liquid, it follows that the rate of separation of solids from solution depends upon the diffusivity of the compound, and on the molecular mobility of the solution.

**Polymorphic Substances.** — When polymorphic crystals separate from liquid phase, or from solution, the kind of crystal phase which separates in a particular instance depends chiefly on the temperature at which saturation and separation take place, and this depends largely on the character of the liquid, or of the solution, its composition and viscosity. It is affected to some extent by the pressure at which separation takes place, and is modified in some instances by the character of nuclei about which the substance crystallizes.

Thus it has been found in the laboratory[1] that five crystal phases of magnesium metasilicate, $MgSiO_3$, may be obtained from the liquid phase under different conditions as follows: 1. An orthorhombic form is obtained by very sudden chilling of the liquid at about 1525°. This is enantiotropic with the second form at 1365°. 2. A monoclinic pyroxene of this composition is formed by crystallizing a melt below the transition point, 1365°, which may be readily accomplished by slow cooling. 3. An orthorhombic pyroxene identical with enstatite crystallizes at lower temperatures than

[1] Allen, E. T.; White, W. P.; Wright, F. E.; Larsen, E. S. Amer. Jour. Sci., vol. 27, 1909, pp. 1–47.

that at which the monoclinic form crystallizes. It may be formed by heating the glass of this compound at a temperature between 1000° and 1100°. It also forms in silicate solutions similar to rock magmas. 4. A monoclinic crystal phase corresponding to an amphibole forms in very small quantities by rapidly cooling the liquid phase. 5. An orthorhombic amphibolic form is obtained by heating the molten silicate high above the melting point, to about 1600°, and then cooling rapidly in air. The three last crystal phases are monotropic with respect to the two first and pass into them upon heating.

**The Order of Separation** of several compounds from solution depends on the degree of saturation of each, that with the highest degree of saturation, or that one whose saturation point is reached first upon the cooling of the magma solution, separates first.[1] The relation of saturation to molecular concentration and to the melting point, or crystallizing point, of the compounds in solution has been thoroughly investigated and will be stated for the several groups of cases which may possibly occur.[2]

(1) For the case of two compounds, which when liquid are miscible in all proportions, the relation between saturation, melting point of each compound, and the proportions of each in the mixture, may be indicated by a diagram, Fig. 1. In this the relative proportions of the compounds A and B are given by the abscissas, temperatures by the ordinates. The solidifying point of A when free from B is at $T_a$, that for pure B is at $T_b$. When B is added to liquid A the solidifying point is lowered, and the line $T_aE$ shows the solidifying points for mixtures of the two as the amount of B increases. Likewise when A is added to liquid B the solidifying point is lowered

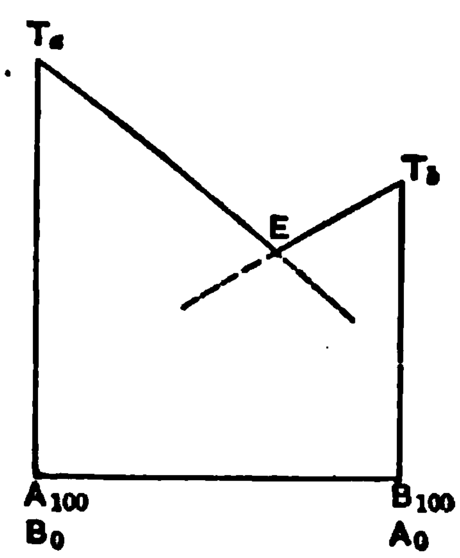


FIG. 1.

[1] This subject has been specially treated by J. H. L. Vogt in a series of publications, the more important of which are: Die Silikatschmelzlösungen mit besonderer Rücksicht auf die Mineralbildung und die Schmelzpunkterniedrigung. I. Über die Mineralbildung in Silikatschmelzlösungen. II. Über die Schmelzpunkterniedrigung der Silikatschmetzlösungen. In Christiania Videnskabs Selskabs Skrifter, math. naturv. Klasse, 1903, No. 8, and 1904, No. 1. Also Physikalisch-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen. Tscher min. petr. Mitth., vol. 24, 1906, pp. 437–542.

[2] Meyerhoffer, W. Zeitschr. f. Kryst. u. Min. 1902.

and the line $T_bE$ shows the changes in solidifying point as A increases in amount. At $E$ there is a minimum temperature at which both may solidify at the same time. This is called the EUTECTIC POINT, and the proportions of A and B corresponding to this point is the EUTECTIC MIXTURE, or the particular mixture of the two compounds which exhibits the lowest melting point. In general the lines of solidifying points are not straight but somewhat curved.

The position of the eutectic point between the extremes of the diagram, $AT_a$ and $BT_b$, depends upon the melting points of the substances A and B, their heat of fusion or liquefaction, molecular weight and ionic dissociation.[1]

If all these factors were alike in the two substances the eutectic point would lie half way between the extremes, and would correspond to an equal mixture of A and B. When the melting points of A and B are unlike, the other factors being alike, the eutectic point will be nearer the substance with the lower melting point as in Fig. 1. The same is true for its relation to the heat of fusion, other factors being alike. That is, the eutectic point will be nearer the substance with the lower heat of fusion. In general, the heat of fusion increases with the melting point for pyrogenetic mineral compounds, so that these two factors operate in the same direction. They are also considerably more effective than the others, because a substance with high melting point commonly possesses a correspondingly high heat of fusion. When the factors just mentioned are alike for both substances the eutectic point is nearest that with the highest molecular weight and the highest ionic dissociation. But the influence of these factors on the position of the eutectic point and the composition of the eutectic mixture is generally inconsiderable. So that the dominant relationship in magma solutions is between the eutectic point and the melting point of each component.

In the case under discussion the process of separation of the components, A or B, from the solution may be followed by reference to Fig. 2. If the point $m$ by its position indicates the proportions of A and B in a given mixture, about .6 A + .4 B, and also the temperature, then as heat is lost the mixture cools to the temperature, $t$, when it will be saturated with A, which upon further cooling will separate if supersaturation does not set in. With separation of A the composition of the mixture changes toward greater amounts of B. The action with falling temperature follows the curve $T_aE$ until it reaches the eutectic point $E$, when the solution is saturated both with A and B. And if supersaturation with the second substance, B, does not

[1] Vogt, J. H. L. Die Silikatschmelzlösungen, II, 1904, p. 128, *et seq.*

take place, both substances must separate at the same time upon further fall of temperature, the composition of the mixture remaining constant until separation and solidification have been completed.

Should the mixture originally consist of A and B in the proportions indicated by the position of the point $n$, about .2 A + .8 B, then as temperature falls, when $t'$ is reached the solution is saturated with B, and this substance separates upon further cooling until the composition of the mixture reaches the eutectic

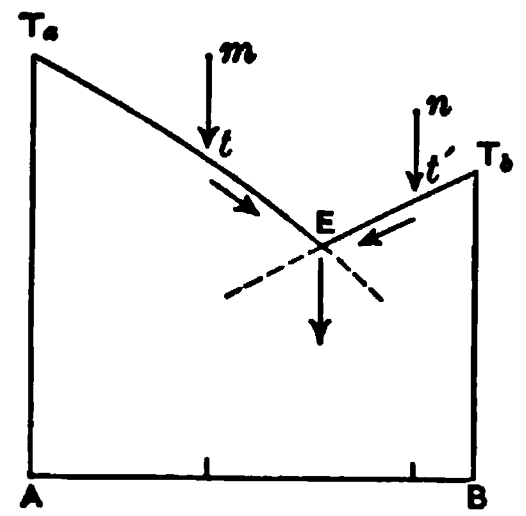



FIG. 2.

mixture at $E$, when both components A and B separate at the same time. The final crystallization after the eutectic point has been reached is the same in all possible mixtures of A and B when no other substance is present, and supersaturation with respect to either component does not take place.

The order then in which two components separate from a solution is dependent on their relative proportions, taken in connection with their relative melting points, heats of liquefaction, molecular weights, and ionization in solution. It is always possible to vary the proportions so that one or the other may separate first. And the nearer the eutectic mixture of the two is to one of equal parts of each the greater will be the possibility of either separating before the other in mixtures of the two. In cases where one component has a much higher melting point than the other the possibility of its separating first from differently proportioned mixtures is proportionately increased.

In case supersaturation takes place before crystallization of one of the components the process of separation may be traced in the diagram, Fig. 3, as follows: a solution whose compo-

sition is indicated by $m$ cools below $t$, the point of saturation with A, until supersaturation has taken place and the temperature reaches $s$, when separation of A sets in. This proceeds without change of temperature, generally, until equilibrium is restored at the point of saturation $r$, when the process will follow the line to $E$, for supersaturation with A cannot again take place because of the presence of A in the solid phase, unless the rate of cooling is relatively great. When $E$ is reached it may happen that B fails to separate, and supersaturates the solution until a point $d$ is reached, when B begins to separate. The process may now follow one of several courses. (a) B and

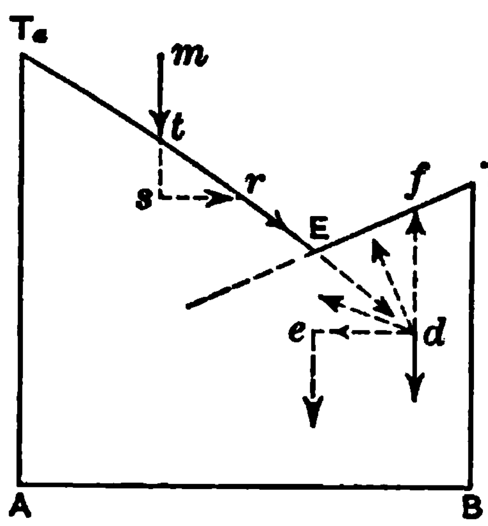



FIG. 3.

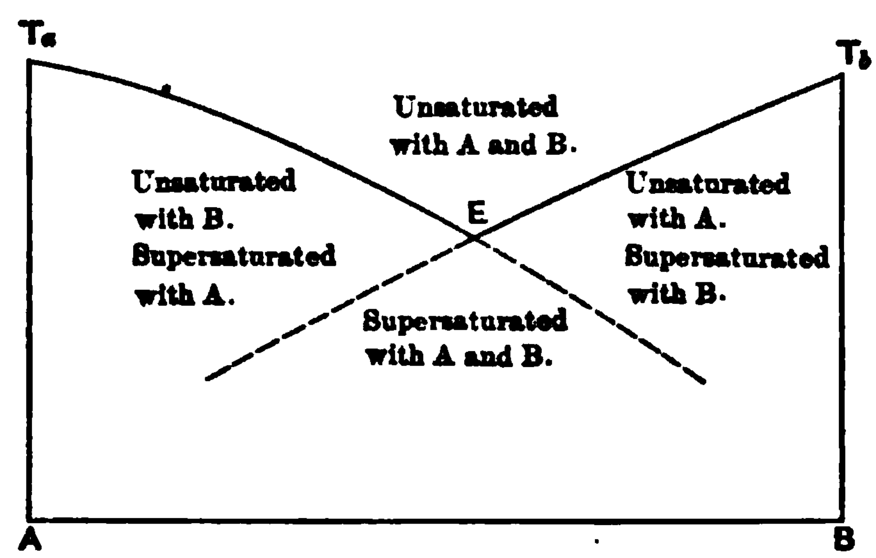



FIG. 4.

A may both separate simultaneously until complete separation is attained. (b) B may separate at stationary temperature, the further separation of A being suspended, until the point $e$ is reached, when both separate together. (c) At the point $d$, B may start to separate at such a rate that the release of heat of fusion may notably raise the temperature of the solution. In such a case it is possible for solid A to pass back into solution until this returns to the proportions of the eutectic mixture either at the point $E$, or at some temperature between $E$ and $e$, dependent on the rate of heat liberation; or it is possible for A to remain undissolved, or inappreciably so, while the temperature of the solution rises until it meets a saturation point for B on the line $T_bE$, somewhere between the composition of the eutectic mixture and that of the solution when the separation of B began, indicated by $f$.

The partial melting of one solid component through rise of temperature due to heat liberated by the rapid separation of

another component, probably takes place to some extent in rock magmas, and will be referred to again.

The relations of temperature, concentration of two components, and supersaturation of each, are indicated in Fig. 4, and need no further description. From this it is evident that when the curves $T_aE$ and $T_bE$ have nearly the same direction, that is, when there is but slight difference between the melting points of each component and the eutectic point, Fig. 5, it is easily possible upon cooling a mixture of the two for supersaturation of one component to take place and persist until the second component saturates the solution, when it may begin to separate before the other.

**Effect of Supersaturation on Order of Separation.** — Further elaboration of this discussion relates to the possibility of separation taking place in the metastable, or labile, condition of the

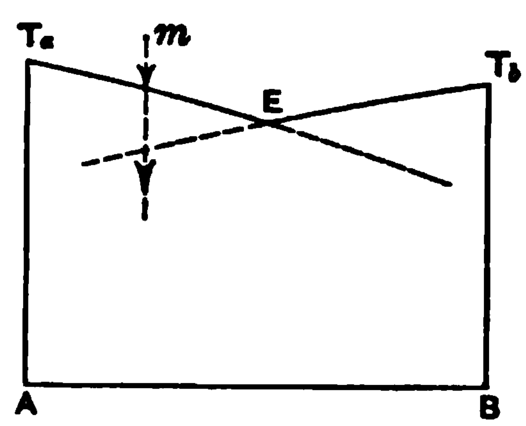



FIG. 5.

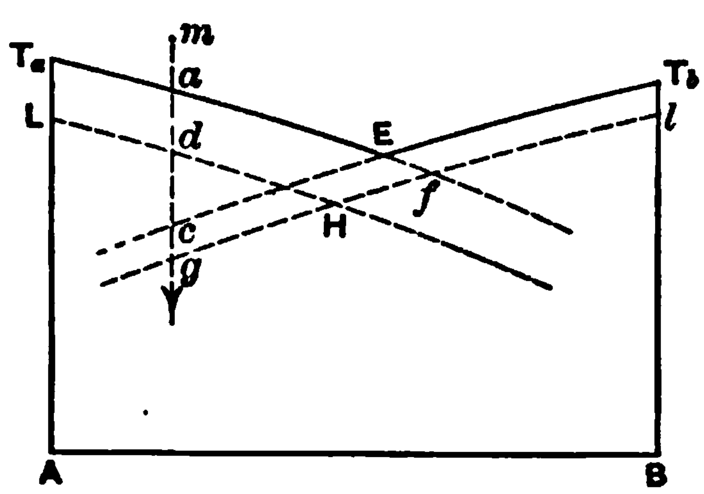



FIG. 6.

solution with respect to each component. This has been investigated for certain mixtures by Miers[1] with the following results, Fig. 6.

The melting, or saturation, point curve $T_aET_b$ denotes the temperatures at which separation of A or B may begin to take place from different mixtures of A and B. In case the solution has the composition indicated by the position of $m$, then upon cooling to $a$, separation may begin, or supersaturation of the solution may set in. The solution may enter the metastable condition with respect to A. This may continue until the temperature reaches $d$, a point on the curve of *spontaneous crystallization*, or the *supersolubility* curve, to use Miers's term. This curve is nearly parallel to that of saturation points and

[1] Miers, H. A., and Isaac, F. Proc. Roy. Soc. A., vol. 79, 1907, pp. 322–351.

corresponds to the transition points from metastable to labile condition in different mixtures of two components. In the metastable condition crystallization may take place from contact with solid; in the labile condition it may be induced to take place by mechanical means, such as agitation. But it does not necessarily happen when the labile condition of a solution has been reached, since it has been demonstrated by Miers that in a closed tube free from every trace of solid phase of a substance separation may be delayed indefinitely even when the solution has reached the labile stage or temperature.

It is possible then for the mixture represented by *m*, Fig. 6, to cool below the temperature *b* without any solid A separating. Upon cooling to *c*, B may separate if solid B is present, or the solution may enter the metastable condition with respect to B, eventually cooling to *g* and entering upon the labile condition with respect to B. In such a case it is labile with respect to A and B at the same time. From this it is seen that under conditions favoring supersaturation it is possible to obtain crystals of A or B in either order, and in each case either by a metastable or a labile mode of separation.

Moreover, the case represented by Fig. 3 is better understood when considered in connection with the existence of the curve of spontaneous separation. For when the separation of A proceeds along the line $T_aE$, and with supersaturation of the solution with B, reaches *f*, Fig. 6, if this is the labile point for B its separation should be rapid, while that of A which is not near its labile point may be slow if the fall of temperature is not too rapid. The bearing of these differences in the rates of separation of two constituents crystallizing at the same time upon the texture of igneous rocks will be discussed in another place. It will be observed in Fig. 6, that the HYPERTECTIC POINT, *H*, is not the same as the eutectic point either as regards temperature or the composition of the mixture.

For a constant rate of temperature change the rate of separation of a substance from solution is undoubtedly related to the degree of supersaturation at which it begins, and this may be expressed by means of a diagram, and the possible process of separation of the components A and B may be indicated as in Fig. 7. From *m* cooling may carry the solution to a point of

supersaturation, $d$, at which rapid separation may take it to $c$, from which it follows the line $T_aE$ into the metastable condition of B until $f$ is reached. This point is near the labile limit for B but is only at saturation point for A. The separation of B would proceed rapidly while that of A continued relatively slowly. This would change the composition of the mixture faster with respect to B than to A, consequently the line from $f$ toward $H$ would represent the changes in composition of the

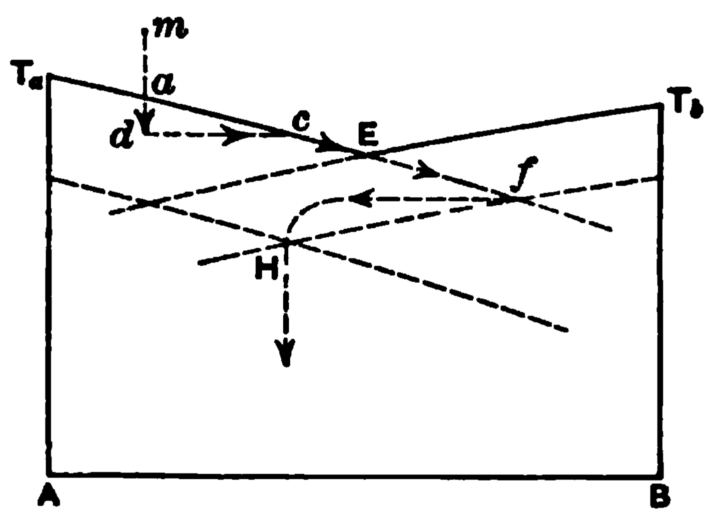



FIG. 7.

mixture, for nearly stationary temperature, which according to the rate of liberation of heat of fusion of B, and the rate of loss of heat from the solution, would cause the line of separation from $f$ to move horizontally, to rise, or to fall toward $H$. According to the rate of separation of B as compared with that of A, the amount of A in solution varies, its supersaturation setting in under the assumption of the case under discussion. With its supersaturation its rate of separation would increase until equilibrium is established between the solubilities of A and B, their proportions, and the temperature of the solution. This must lie in the direction of the hypertectic point $H$. The final separation of the components A and B will take place then more nearly according to the hypertectic proportions than the eutectic proportions.

It is evident from the foregoing discussion that from mixtures of two independent miscible components separation may take place in either order, at variable rates for each component, and that the final act of crystallization may be quite different in different cases according to the degree of supersaturation attained for each component. The probability that any particular mode of separation will take place with greater fre-

quency than others in various rock magmas must be determined by observation and experimentation, and will be considered more fully in the discussion of rock textures.

**Separation of Isomorphous Compounds.** — When two components, miscible in all proportions in the liquid state, are capable of forming mixed isomorphous crystals, the process of separation from solutions of the two is somewhat different from that just described. Several cases arise according as the two components (*A*) can form an unbroken series of mixed crystals, or (*B*) cannot form a continuous series.[1] Examples of these cases occur among the mineral compounds in igneous rocks. The process of separation may be discussed by means of a diagram similar to those already used in which the ordinates are temperatures and the abscissas concentration, or proportions of the two components, A and B, Fig. 8. Since the solids separating are solid solutions, as already pointed out, and the concentrations of the components in the solid and liquid phases are not the same in general for like temperatures, it follows that two transition curves are necessary for each system, one relating to the liquid phase, the other to the solid phase.[2] The temperature at which solid begins to separate from the liquid solution may be called the *freezing point* of the liquid, and that at which the solid solution begins to liquefy may be called the *melting point* of the solid solution. The temperature-concentration curve for the liquid phase will therefore be the freezing-point curve, sometimes called the *liquidus,* that for the solid phase will be the melting-point curve, or *solidus.* The latter is designated in the diagrams by a broken line.

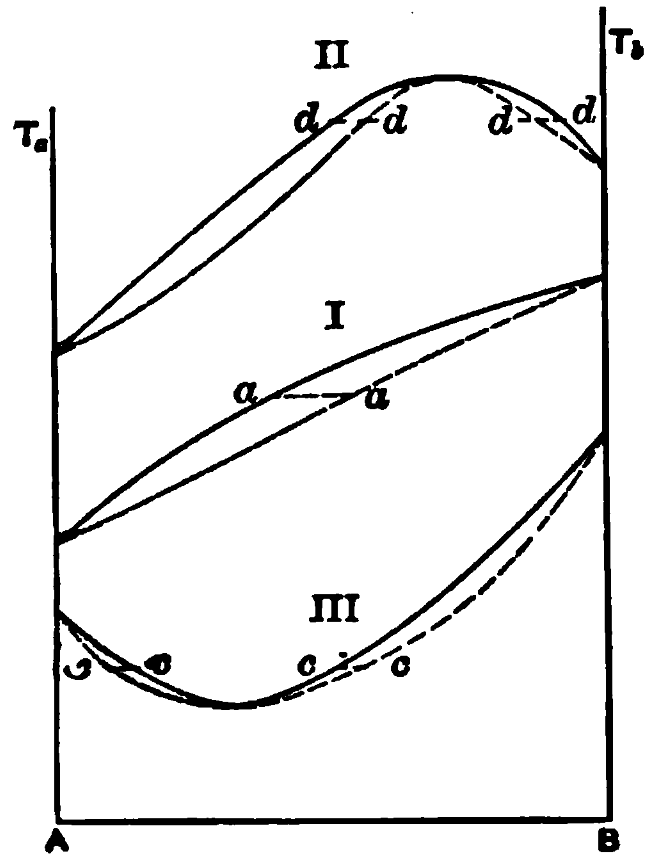



Fig. 8.

(*A*) In the case under discussion, since there is a *continuous series of mixed crystals* possible between the extremes, the equi-

[1] Roozeboom, H. W. B. Zeitschr. f. phy. Chem., vol. 30, 1899.

[2] Findlay, Alex. The Phase Rule, 1904, p. 180.

librium curve must be continuous. The possible variations in types of processes of separation under these conditions are three, which are represented in the diagram, Fig. 8. I. The freezing points of all mixtures lie between the freezing points of the pure components A and B. II. The freezing-point curve possesses a maximum. III. The freezing-point curve passes through a minimum. The same is true of the melting-point curves in each type as shown in the diagram, and since they lie below the corresponding freezing-point curves, and are tangent to them at the maximum and minimum points, it follows that at any given temperatures, such as at *a*, *d* and *c*, in the different

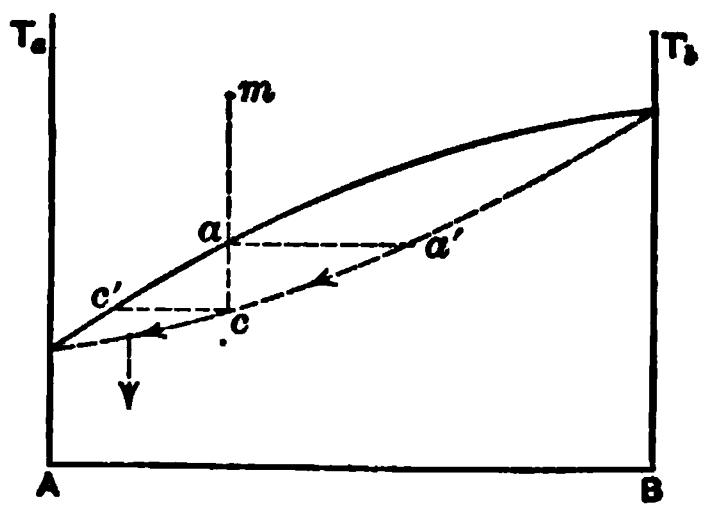



Fig. 9.

types, *the concentration of that component, by the addition of which the freezing point is depressed, is greater in the liquid than in the solid phase;* or, conversely, *the concentration of that component, by the addition of which the freezing point is raised, is greater in the solid than in the liquid phase.*

In consequence of this relation the composition of the mixed crystal separating from a solution of two components is generally different from that of the solution from which it separates, as may be seen from Fig. 9, representing a case of the first type. When a solution, whose composition is indicated by the position of *m*, cools to the temperature *a*, the solid mixed crystal that is in equilibrium with the solution at this temperature is at *a′*, and its composition differs from that of the solution at this temperature by a greater amount of B. As the temperature falls, the corresponding freezing points of the liquid would be found along the line *ac′*, but the compositions of the successive mixed salts, separated from solution, would follow the curve *a′c*, that is, they would

become gradually richer in A, as separation progressed. When solidification is complete the average composition of the mixed crystals must equal the composition of the whole solution at the beginning of separation, which is indicated by the position of *m* in the diagram. But as the first of these are richer in B than the solution, the last of them must be richer in A than the original solution. The final separation must take place with a concentration nearer to A than *c* is in the diagram.

In Type II, in which a maximum separating point exists between the extremes of the pure components, the addition of either to a pure liquid of the other must raise the freezing point. This is a very rare occurrence, and it is not known that any mineral compounds formed in igneous rocks are of this type.

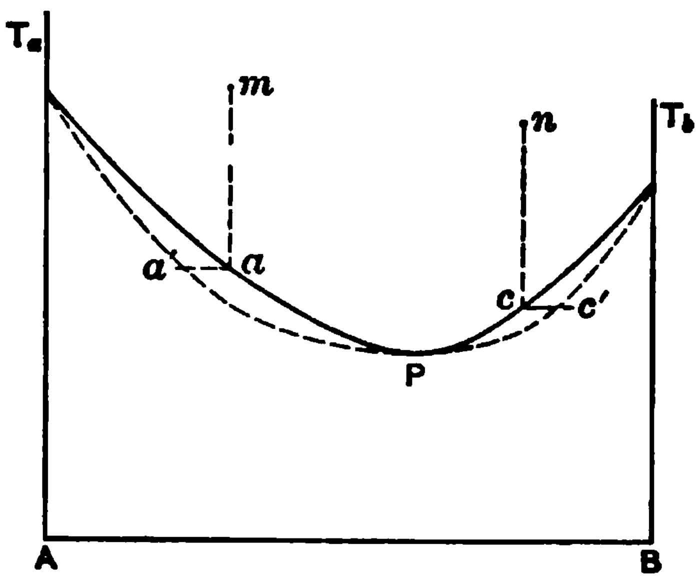



Fig. 10.

In Type III, with a minimum freezing point for certain mixtures of two components, there is a resemblance to the general case of two compounds that do not form mixed salts. But instead of a eutectic point at the intersection of two curves, there is one continuous curve through the minimum point, at which the mixed crystal would separate with the composition of the liquid, and would exhibit a definite melting point. For solutions on either side of this point the separating mixed crystals would contain more of one component, or of the other, than the solution contained.

Thus, in Fig. 10, from a solution at *m*, when cooled to *a*, crystals would separate relatively richer in A than the solution, and with continued cooling they would become richer in B until the minimum point, *P*, is reached, when the solution would solidify

with this composition, provided it had not completely solidified before this point was reached. On the other hand, from a solution, at *n*, when cooled to *c*, crystals would separate relatively richer in B than the solution, and upon further cooling they would become richer in A until the point *P* was reached, when the remainder of the solution would solidify with a composition corresponding to this point in the diagram. That is, in each of these cases the end result might be the same, though approached from opposite directions. The occurrence of mixed crystals exhibiting this variation in zonal structure should be a proof that the components belonged to this type of isomorphous compounds. It is a question whether this type is represented among the pyrogenetic minerals.

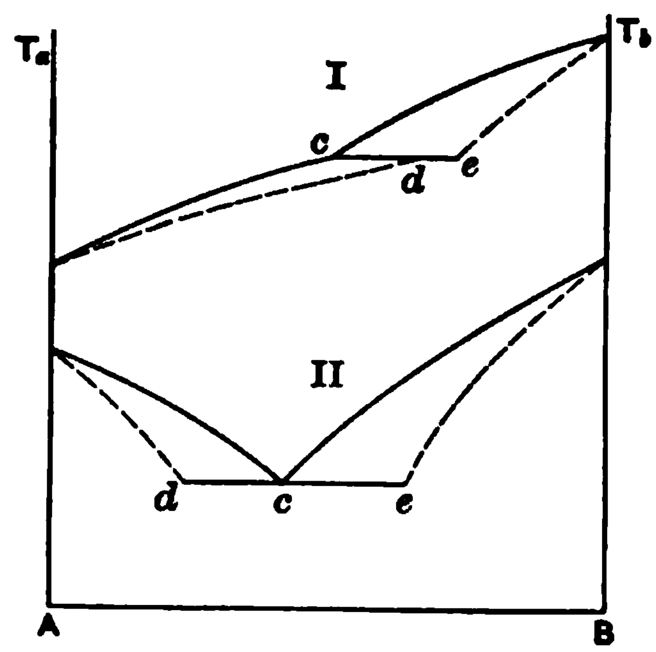



FIG. 11.

(*B*) *When the two components do not form a continuous series of mixed salts,* the case is similar to that of liquids not miscible in all proportions. Crystals of A can take on variable amounts of B up to a certain amount, and crystals of B can take on variable amounts of A up to a certain limit; while in the liquid phase they are miscible in all proportions. In this case there are two types of variation.

I. *The freezing-point curve exhibits a transition point,* as at *c*, curve I, Fig. 11. It resembles the first type shown in Fig. 8, but the rate of change of freezing point with concentration is not uniform, there being a change of rate at the point *c*; and the rate of change of concentration in the solid solutions being still more diverse, the melting-point curves do not meet when the temperature is at *c*, but pass through the points *d* and *e*, so that at tem-

perature *c*, two concentrations of mixed salts, corresponding to the points *d* and *e*, are in equilibrium with the liquid solution.

II. In the second type *the freezing-point curve exhibits a eutectic point*, as at *c*, curve II, Fig. 11. This resembles Type III, Fig. 8, except that the curves corresponding to the concentration in the solid solutions do not meet at the eutectic point, but pass through points *d* and *e*, for the temperature at *c*, Fig. 11, so that at this temperature two concentrations of mixed salts are in equilibrium with the liquid solution. Examples of isomorphous compounds that under the conditions attending the cooling of rock magmas do not form unbroken series of mixed crystals are found in potash-feldspar and lime-soda-feldspars. Though similar chemically, and crystallizing in similar forms, they usually constitute distinctly different mixed crystals, potash-feldspar often containing variable amounts of soda-feldspar, and still less of lime-feldspar, while lime-soda-feldspars frequently contain small amounts of potash-feldspar.

By analogy with partially miscible liquid solutions, partially miscible solid solutions, which are more miscible at higher temperatures than at lower, may upon sufficient fall of temperature readjust themselves by separating into two solid solutions of different concentration. This transformation, which is known to take place in the solid state in some metallic alloys,[1] has been supposed by some petrologists to take place in certain pyrogenetic mixed solutions, and to result in perthitic intergrowth of potash-feldspar and soda-feldspar. But there is as yet no definite evidence that these intergrowths are not original modes of crystallization from the rock magma.

**Zonal Structure.** — Since isomorphous compounds commonly crystallize about one another in parallel molecular arrangement, the first mixed crystals of A and B, richer in B, will be surrounded by successive shells of mixed crystals containing more and more A. This produces a zonal structure in the isomorphous compound crystal, which may show itself in differences of color, of refraction, and of other optical properties. The commonest examples of such zonally built pyrogenetic crystals are furnished by the lime-soda-feldspars.

[1] Roberts-Austen and Stansfield, Rapports du congrès international de physique, 1900, I, p. 363.

When temperature falls rapidly it may pass so quickly from *a* to *c*, Fig. 9, that the mixed crystals will separate with the same composition as the liquid solution; they will have a uniform composition throughout and will not exhibit zonal structure; or should supersaturation take place with slow cooling, and the temperature reach *c*, or less, the mixed crystal will have a uniform composition like that of the solution. The first case is realized when lime-soda-feldspars are crystallized in the laboratory.[1] In this case no zonal structure is developed. The second case is probably realized in coarse-grained rocks rich in lime-soda-feldspars, gabbro and anorthosite, in which the feldspars are without zonal structure, that is, are of uniform composition.

Referring to Fig. 9, it will appear that there may be irregular variation in the composition or concentration of successive mixed crystals, or of zones in a zonally built one, since the composition at a particular temperature also depends upon the rate of change of temperature. For if with rapid cooling a homogeneous mixed crystal may form, having the composition at *c*, and with slower adjustment one may separate having the composition at *a′*, then with variable conditions mixed crystals having any intermediate composition may form. Should variations in the temperature take place in an irregular manner during the separation or crystallization of solids there might be produced successive shells, or zones, not only of notably different concentrations in one direction, producing irregular steps, or stages, instead of a gradual transition from zones, or crystals, richer in B toward those poorer in B, but there may be produced zones, or crystals, exhibiting a recurrence in degrees of concentration, that is, reversing the order of separation. For a mixture near *c* might be followed by one nearer *a′*. This alternation of zones is often noticed in the lime-soda-feldspars, and stepped zones with distinct optical differences are those most frequently developed in these minerals. Several causes can be found to affect variation in the rate of cooling of rock magmas, such as changes in position during eruption, affecting rate of loss of heat by conduction and change of pressure, also variation in the liberation of heat of fusion upon the crystallization of minerals.

[1] Day, A. L., and Allen, E. T. Isomorphism and Thermal Properties of the Feldspars. Publ. Carnegie Institution, Washington.

**Eutectic Mixtures of More than Two Components.** — If to a solution of two components in one another, which may separate into the pure solids without the production of mixed salts or new compounds, there be added a third component behaving in like manner to the first two, then the freezing points of the ternary solution will be lower than those of the first, and a minimum or *ternary eutectic* point will exist, for which there will be a particular concentration of the three components, which will separate at the same time, if supersaturation does not take place. This relation between temperature and concentration for three components may be illustrated by the diagram, Fig. 12. In this it is seen that the point $E_{abc}$ will lie below

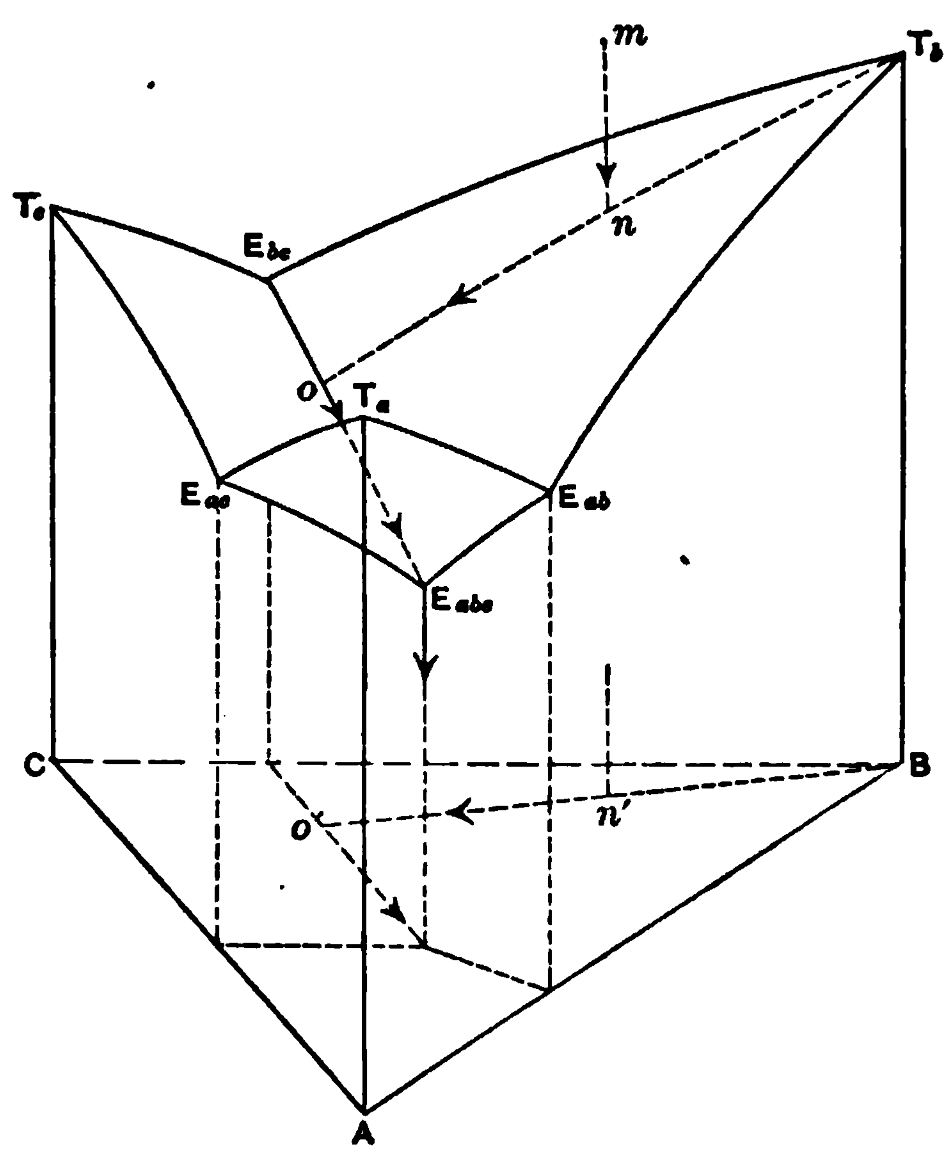



FIG. 12.

all of the other eutectic points, $E_{ab}$, $E_{bc}$, $E_{ac}$, between each pair of components, A and B, B and C, A and C. The normal projection of these on the basal triangle $ABC$ shows the concentration of each component in the four eutectic mixtures, one of which is ternary, at $E_{abc}$. From this, when represented in a simpler manner as in Fig. 13, it is seen that the concentration of

A and C is not the same in the ternary eutectic mixture, $E_{abc}$, as it is in the binary one, at $E_{ac}$. In other words, the concentration of any two components that may enter a eutectic mixture varies with the character of other components that may enter the solution.

The process of separation in a ternary solution may be followed by means of the diagrams, Figs. 12 and 13. If *m* indicate by its position the temperature and composition of a ternary solution, consisting approximately of .3 A, .6 B, and .1 C, then upon cooling to the point *n*, if supersaturation does not set in, B in solid phase will begin to separate, and will continue to do

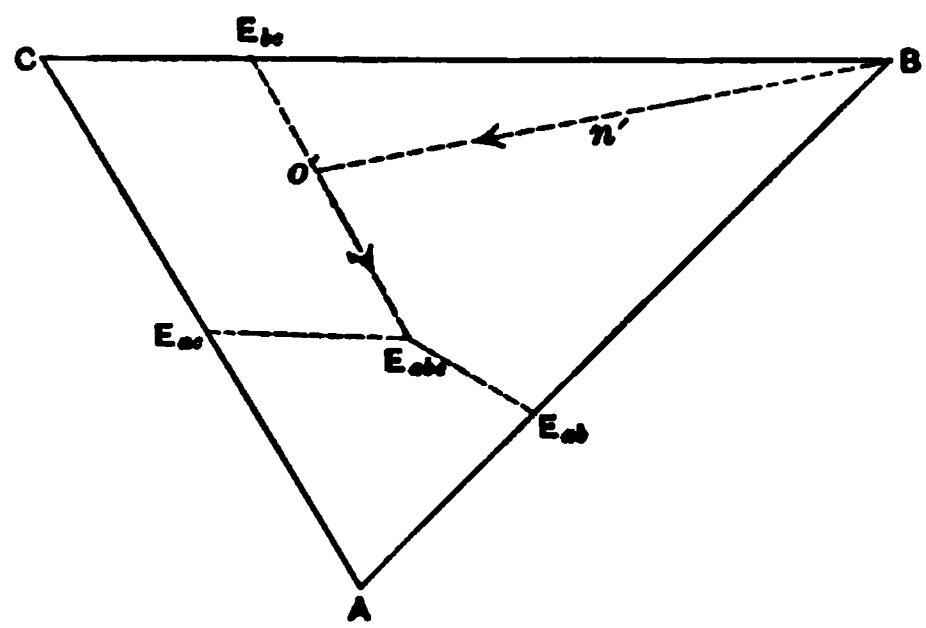



FIG. 13.

so as temperature falls to the point *o*, when C will also begin separating along with B, as in a eutectic mixture, but at different concentration from what it would have at $E_{bc}$. This is owing to the presence of the third component, A. B and C continue separating at different rates, changing the ratio between them until the temperature at $E_{abc}$ is reached, when A begins to separate along with B and C; the solution then having the eutectic concentration for these three components. In Fig. 13, the path followed by the curve of separation $n'o'$ lies along the line connecting $n'$ with B, since the ratio between A and C must remain unchanged while B alone is separating from the solution. In like manner the process of separation may be traced for the case of any solution of three components when supersaturation does not take place.

In case there is supersaturation, the process will be modified in a manner analogous to that discussed for supersaturated

binary solutions. And as this may happen in cooling rock magmas the possibility of a *ternary hypertectic* mixture and temperature must be kept in mind.

When there are more than three independent components capable of separation in solid phase the discussion becomes more intricate because of the difficulty of introducing four or more coördinate factors into a plane diagram. The process may be imagined more or less correctly, however, and the general statement made that, according to the concentration of the components in the solution, upon cooling a temperature will be reached at which one component, two components, or more, will begin to separate from the solution. If the concentration happened to be just that of the eutectic mixture of all the components, and there were no supersaturation by any component taking place, then all would begin to separate at once, and continue crystallizing at the same time.

In case one component only separated at first, it would continue to do so alone until the concentration and temperature were such that another component reached the point of saturation, when it would join the first and separate at the same time as temperature fell, and so on until all components were separating, that is, crystallizing. Theoretically each component should remain in solution to a certain extent until the final eutectic mixture is reached, the extent depending on the solubility relationships. But the amount remaining in solution may be inappreciable in some cases, when it is customary to say that the substance has entirely separated in solid phase.

The process of separation from a complex solution, such as most rock magmas, is further complicated by the formation of mixed crystals in the manner already described, and by the molecular decomposition and chemical recomposition of various compounds during the cooling of the solution, as when amphiboles, micas, and other mineral compounds are affected.

From the foregoing it appears that the solidification with crystallization of rock magmas must be an extremely intricate process, involving variable or irregular changes in temperature and pressure consequent on the movements of eruption, together with variations in composition chiefly through changes in gaseous components, and the possibilities of chemical reaction

among the components with changing chemical equilibria, and the probabilities of supersaturation of the magma by different components to various degrees. And while on this account, and because of the present imperfect knowledge of the chemical and physical constants of many of the pyrogenetic compounds, it is not possible to treat the problem of rock crystallization in a strictly quantitative manner, still it may be possible to point out the salient features of the process in a general way and treat it in a qualitative manner. This will be attempted in certain instances in the following pages. For special discussions of the problem the student is referred to writings by Vogt,[1] Doelter,[2] and by Day and his colleagues in the Geophysical laboratory of the Carnegie Institution of Washington already cited.

[1] Vogt, J. H. L. *Die Silikatschmelzlösungen.* Videnskabs-Selskabets Skrifter, I. Math.-naturv. Klasse, 1903, No. 8, and 1904, No. 1, Christiania, and other papers.

[2] Doelter, C. *Physikalisch-chemische Mineralogie,* Leipzig, 1905, also *Petrogenesis,* Braunschweig, 1906.

# CHAPTER VI

## CRYSTALLIZATION AND TEXTURE OF IGNEOUS ROCKS

**Introduction.** — When a substance separates from liquid solution in solid phase it crystallizes, that is, its molecules arrange themselves in some one of the regular, more or less symmetrical structures characteristic of crystals. They do not form amorphous bodies like glass. This is only produced by a reduction of molecular mobility, an increase in viscosity, such that crystal molecular arrangement is prevented. As already said, rock glass is produced by the relatively rapid cooling of rock magma, and is a final stage in its solidification. It commonly forms after some components of the magma solutions have crystallized, but it does not separate in a solid state from liquid magma, and only forms as the solidification of the remaining liquid.

Since some rock magmas are exceedingly viscous as they approach saturation points, so that there is an imperceptible gradation between viscous liquid and solid glass, no line of demarcation exists between liquid and glass. Crystallization may take place in the highly viscous liquid, and it takes place also at very slow rate in the course of great lengths of time in the solid glass. The former is pyrogenetic, the latter is secondary, or subsequent, and is properly *devitrification* in a strict sense. But as hot, highly viscous liquid may be called plastic glass, crystallization in such a body has been called by some devitrification. This is a common custom among manufacturers of commercial glass, and is sometimes followed by petrographers. The term, devitrification, will be used in this book only for crystallization that has taken place in rock glass through secondary causes. The discussion which follows relates to crystallization that takes place directly upon the cooling of rock magmas having any degree of viscosity.

The act of crystallization involves the idea of molecular attraction, together with that of molecular orientation or adjustment by turning, as well as that of a selective character, since mole-

cules of like substance come together to form a crystal, separating themselves by diffusion from the molecules of other substances with which they are homogeneously mingled. The initial impulse must lie in the force of attraction between the solid molecules in solution, this being accompanied by those of orientation. The condensation of several solid molecules into a more compact spacing in the crystal than they possessed in the solution decreases the molecular concentration of the crystallizing substance in the immediate neighborhood of the crystal. This is adjusted by the diffusion of more distant molecules of this substance into the space neighboring the crystal, and if temperature continues to fall and concentration to keep pace with the condensation of the crystallizing molecules, the act of crystallization will continue. If subsequent concentration does not pass saturation, crystallization ceases.

Supersaturation may be imagined as a molecular condition in which the uniformly spaced molecules of a substance being like distances apart exert equal attractions on each other in all directions, so that no two can come closer together than others. They all may become gradually closer as supersaturation increases without disturbing the equilibrium of the attractive forces. Anything that will destroy this, like the superior attraction of a crystal solid of the same substance, or an unequally distributed molecular movement, brought about by a sudden jar, will permit the molecules to cluster together. The greater the intermolecular tension, the quicker the reaction and the greater the number of clusters of molecules, that is, the greater the number of centers toward which molecular condensation will take place. The greater the number of centers of crystallization, the greater the number of crystals in a given volume and the smaller their size.

The extent to which a rock magma may have crystallized upon cooling, or may have passed into an amorphous rigid state, or glass, not only affects the mineral constitution of the resulting rock but its physical character and its appearance on a surface, or in section. This appearance, which is derived from the mineral components, and from the groundmass of dense or glassy rocks, is called its *texture*, and may be thought of as consisting of three kinds of features or factors: (1) the degree or extent of

crystallization — the *crystallinity;* (2) the magnitude or size of the crystals — the *granularity;* (3) the shape and arrangement of the crystals and amorphous parts — the *fabric.*[1] Each of these factors will be discussed at length.

## CRYSTALLINITY

Since all kinds of rock magmas under favorable conditions may solidify into crystallized substances, minerals, without any residuum of amorphous glass, and all of these substances or the magmas themselves may be solidified by rapid cooling into glasses without crystals, it follows that between the extremes mentioned all degrees of crystallinity are possible. However, in the solidification of all kinds of rock magmas are all degrees of crystallinity equally likely to occur? The answer to this question will be found in a consideration of the factors involved in crystallization. These are: (1) the molecular mobility, viscosity, of the liquid magma, and (2) the rate of cooling. The viscosity depends upon the chemical composition of the liquid and on temperature, and to a less extent on pressure. By the chemical composition of the liquid is meant its composition in the most complete sense, involving constituents that appear in solid phase in the rocks, and those that may not be visible in the rocks, or may have escaped during the solidification of the magma, chiefly gases.

**Effects of Viscosity.** — The relation between viscosity and composition of magmas is shown by a comparison of the fluidities of different melted pyrogenetic minerals, and of rock magmas, at temperatures near the freezing point. Such substances as liquid quartz, orthoclase, albite, or magmas composed chiefly of these compounds, are extremely viscous as they approach crystallizing temperatures, the observations of Day, already alluded to, having shown that albite glass and the crystal at the melting or freezing point have essentially the same high viscosity or solidity. The same is undoubtedly true of orthoclase and of quartz. Attempts to crystallize these minerals from their liquids in open crucibles have failed, and the frequent occurrence of glassy rocks — obsidians — composed chiefly of these compounds

[1] Cross, Iddings, Pirsson and Washington, Jour. Geol., vol. 10 (1902), p. 611, and vol. 14 (1906), p. 692.

is well known. On the other hand, liquids of anorthite, or strongly calcic feldspars and pyroxene, or the magmas composed chiefly of these compounds are much more fluid at temperatures near their solidifying points, and crystallization readily takes place in such liquids in open crucibles, and rock magmas composed of these compounds commonly crystallize fully, and seldom form rock glasses, unless chilled very quickly. Thus rock glass is oftenest produced in igneous rocks rich in silica, with alkalic feldspars, is frequently produced in those composed almost wholly of alkalic feldspars, and is less and less frequent as the rocks contain more and more calcic and ferromagnesian compounds.

**Effects Due to Dissolved Gases.** — The rôle played by gases, notably $H_2O$, in modifying viscosity and therefore crystallinity is shown by the increase of viscosity upon escape of gas from melting magmas. Obsidian may be melted before an oxy-hydrogen blowpipe with evident fluidity and signs of ebullition as some of the components escape as gas, but after cooling the resulting glass is with difficulty melted by the same flame and is extremely viscous, scarcely moving before the current blown against it. The difference in viscosity between the two melting glasses is strongly marked, but no direct determinations of the viscosity of different silicate glasses with, and without, dissolved gases have been made.

The effect of gases upon crystallization in rock magmas is plainly shown in the more siliceous and more glassy rocks. In the case of the highly siliceous obsidian at Obsidian Cliff, Yellowstone National Park,[1] it has been demonstrated that gases were irregularly distributed in the magma, causing irregularly distributed bubbles in the pumiceous part of the lava and in more compact portions near the pumice, and in these portions the distribution of minute crystals conforms to that of the bubbles in the more pumiceous parts; indicating that where there was more dissolved gas the conditions were more favorable for crystallization than in other parts of the magma. For the latter became too viscous to crystallize owing to rapid cooling, but the portions with more gas, being more fluid at the same temperatures, permitted the molecular diffusion and orientation necessary for crystallization. If greater fluidity due to the presence of gas results in greater ease in crystallization, the separation of anhydrous compounds like quartz and feldspars from a magma containing gas must increase the concentration of the gases in the immediate vicinity of the crystals, and still further promote molecular mobility and ease of crystal arrangement. This may lead to

[1] Iddings, J. P. Seventh Ann. Rep. U. S. Geological Survey, 1888, pp. 283–287.

rapid crystallization about certain points or spots in a magma which may show itself in various ways, the most characteristic of which, perhaps, is in radiating crystals called spherulites which are described on page 228.

**Effects Due to Rate of Cooling.** — The relation between rate of cooling and the amount of crystallization, or crystallinity, in silicate solutions has been plainly indicated. The faster the cooling, the more chance of preventing crystallization by a too rapid increase in viscosity. The loss of heat having effect is that between the temperature at which crystallization may begin and that at which too great viscosity sets in, and these points vary greatly with the compounds in solution. Nothing is known definitely as to the actual rates which must obtain in order to prevent the crystallization of various pyrogenetic compounds in rock magmas.

Some idea of the differences may be gotten from experiences in laboratory work. Thus it has been found that 100 grams of liquid anorthite crystallizes completely in ten minutes to fair-sized crystals, and it requires quick chilling to prevent its crystallization and to produce glass. A mixture of equal parts of anorthite and albite ($Ab_1 An_1$) requires a gradual cooling extending over several days to effect complete crystallization, whereas liquid albite cannot be induced to crystallize through days of cooling in an open crucible.[1] Magmas like basalts have been crystallized by two or three days of cooling.[2]

It rarely happens that rock magmas cool quick enough to completely prevent crystallization of all of the components. But it sometimes occurs in the formation of pumice or lava dust from wholly liquid magmas, and then oftenest from those of the most siliceous and feldspathic kinds. Most rock glasses contain minute crystals in great numbers. It follows from what has been said that glassy rocks are produced oftenest at the surface of the earth where suddenly escaping gases may chill the magma, or where atmospheric currents assist the cooling of compact bodies of lava. They less frequently are formed as intruded bodies so small, or brought so suddenly in contact with cold rocks, that chilling is possible. The great majority of intrusive rocks and the greater part of most large bodies of extrusive rocks are completely crystallized.

[1] Day, A. L., and Allen, E. T. Isomorphism and Thermal Properties of the Feldspars. Publ. Carnegie Institution, Washington, 1905, p. 40.

[2] Fouqué, F., and Michel-Lévy, A. Synthèse des Minéraux et des Roches, Paris, 1882.

**Descriptive Terms Applied to Crystallinity.**[1] — A number of terms describing more or less exactly the crystallinity of igneous rocks have been in use in petrography. Complete crystallinity is definitely described as HOLOCRYSTALLINE, wholly crystalline; partial crystallinity is expressed by HYPOCRYSTALLINE. The general idea of a rock being more or less glassy is expressed by the terms VITREOUS and HYALINE. When completely glassy it is HOLOHYALINE; when partly glassy, HYPOHYALINE. When the relative amounts of crystalline and glassy components of a rock are to be expressed more definitely this can be done by stating exactly the ratio between them where determinable, and when only an approximate statement of the proportions is thought sufficient for purposes of description the method of using fivefold degrees of comparison adopted in the Quantitative System of Classification may be employed. This results in the following terms which need no further comment:

| | | | |
|---|---|---|---|
| HOLOCRYSTALLINE, | | | wholly crystalline. |
| HYPOCRYSTALLINE or HYPOHYALINE, | PERCRYSTALLINE, | $\frac{\text{crystals}}{\text{glass}} > \frac{7}{1}$, | extremely crystalline with some glass. |
| | DOCRYSTALLINE, | $\frac{\text{crystals}}{\text{glass}} < \frac{7}{1} > \frac{5}{3}$, | dominantly crystalline. |
| | HYALOCRYSTALLINE, | $\frac{\text{crystals}}{\text{glass}} < \frac{5}{3} > \frac{3}{5}$, | crystals and glass equal or nearly so. |
| | DOHYALINE, | $\frac{\text{crystals}}{\text{glass}} < \frac{3}{5} > \frac{1}{7}$, | dominantly glassy. |
| | PERHYALINE. | $\frac{\text{crystals}}{\text{glass}} < \frac{1}{7}$, | extremely glassy, with some crystals. |
| HOLOHYALINE, | | | wholly glassy. |

## GRANULARITY

The size of crystals developed in rock magmas depends on several factors, chief of which is the viscosity of the solution, also the rate of cooling of the magma, and the molecular concentration of the substance.

**Effects of Viscosity.** — The influence of viscosity is shown upon comparing the results of cooling molten feldspars of different compositions.[2] Anorthite, which is quite fluid near its

[1] Most of the textural terms used in this chapter have been published in an article on The Texture of Igneous Rocks by Cross, Iddings, Pirsson, and Washington. Jour. Geol. vol. 14, 1906, pp. 692–707.

[2] Day, A. L., and Allen, E. T. *loc. cit. p.* 40.

crystallizing temperature, upon rapid cooling in 10 minutes in a particular instance yielded crystals 3 to 5 mm. thick, while liquid feldspar with the composition $Ab_3An_1$, oligoclase-andesine, after two days' cooling produced microscopic crystals only 0.005 mm. thick scattered through glass. By this comparison it appears that the more liquid anorthite produces crystals one thousand times as thick as those of $Ab_3An_1$ in about one-three-hundredth the time. It is a general observation that magmas of viscous, highly siliceous character yield rocks often glassy with microscopically minute crystals of quartz and potash-feldspar, when magmas of rather liquid character, low in silica, with much calcic feldspar, which have cooled under nearly the same conditions, yield holocrystalline rocks with crystals half a millimeter thick in some instances.

Since viscosity is a specific character of substances, it varies with the chemical composition. Consequently the size of crystals separating from rock magmas is to a certain extent dependent on the chemical composition of the liquid magma. Anything that promotes the molecular mobility of the magma favors the production of larger sized crystals of any given substance. The presence of gases, then, aids the growth of large crystals, the largest of which, measuring 20 to 30 feet in length, occur in very coarsely crystallized pegmatite rocks, generally considered to have formed from magmas containing more than the ordinary amount of $H_2O$ and other gases.

**Effects Due to the Rate of Cooling.** — The relation between size of crystals and the rate of cooling is seen upon comparing parts of the same body of magma that have cooled at different rates, though it is difficult to eliminate the effects due to differences of viscosity that may have existed in any two cases. It is found that those parts of a magma that have cooled rapidly consist of smaller crystals than parts that have cooled slower. A definite expression of the relation between the two has been attempted by Lane [1] and also by Queneau.[2] Each has discussed the problem on a basis of the theory of the rate of diffusion of heat in a cooling mass without convection currents, and curves

[1] Lane, A. C. Bulletin Geol. Soc. Am., vol. 8, 1897, p. 403. Reports Geol. Surv. Michigan, vol. 6, Part I. Annual Reports Geol. Surv. Michigan, 1903 and 1904.

[2] Queneau, A. L. School of Mines Quart., vol. 23, 1902, pp. 181–195.

expressing the rate of change of temperature at different distances from the margin of a body of magma have been deduced, and are shown in Fig. 1.

In this diagram the ordinates are temperature, the abscissas are time. The different curves correspond to the rates of cooling at different distances from the margin of the mass, the upper curve being that at the center, the lower one that at the margin. The ratio and curvatures represent a special case but allow of some general conclusions, namely: assuming a notable difference between the initial temperature of the magma and that of the

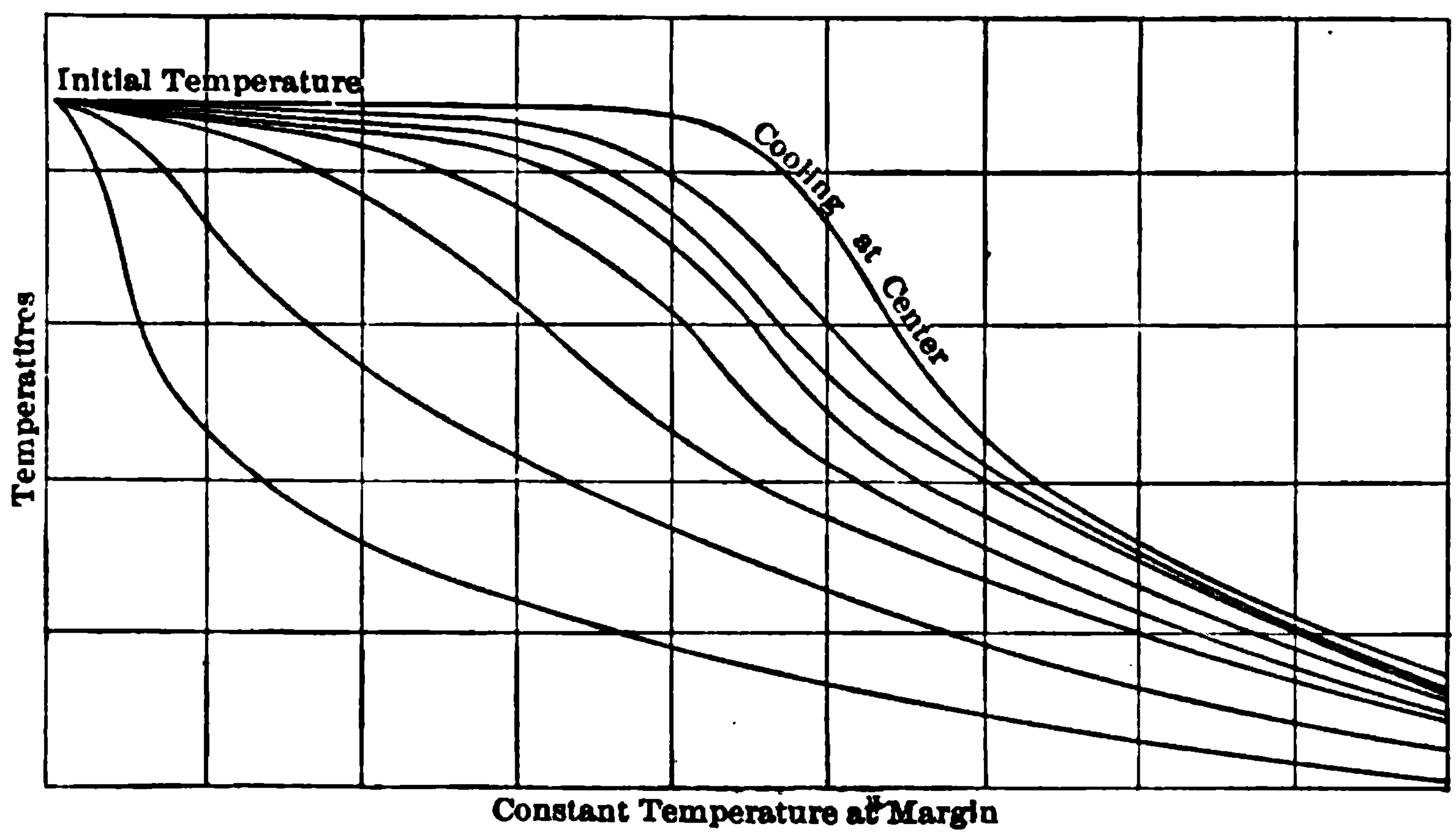



FIG. 1.

adjacent rock, or cooling surface, then at the margin the temperature drops suddenly at first, afterwards slowly; at the center the temperature is at first stationary, then diminishes slowly and then more rapidly. After a lapse of time when a temperature is reached, depending on the thickness of the body of magma and its diffusivity, the rate of cooling at a given temperature is the same in all parts of the body. The rate of cooling becomes constant first at the center, spreading toward the margin and becoming constant at lower and lower temperatures. From this it may be concluded that if a considerable period of time elapses before any part of the body attains the saturation point, the rate of cooling will have become the same throughout the mass and, other things being alike, the grain of the rock will not

vary. There will be more variation of grain the nearer the initial temperature is to the point of saturation of the magma solution, and the lower the temperature of the adjacent rock at the time of eruption of the magma.

It also appears from the equation for the diffusion of heat that the time of cooling of a sheet, or dike, of magma varies as the square of the thickness of the sheet. Also the time required for a given drop of temperature for any point varies as the square of its distance from the margin, provided the center has not perceptibly cooled. If, then, the sizes of the crystals are proportional to the time required for a given drop of temperature, and the areas of such crystals in a rock section correspond to their size, it follows that the square roots of the areas, their average diameters, vary directly as the distance from the margin, so far as their size is dependent on the rate of cooling of the magma.

Measurements by Queneau of certain crystals in several rock bodies at measured distances from the margin showed a remarkable confirmation of the relationships just stated. It is, of course, necessary to consider those crystals only that have begun to crystallize after the magma has come into the position in which it solidified.

**Effects Due to Molecular Concentration.** — The size of crystals is dependent on the molecular concentration, or amount of substance in solution, since the rate of separation of solid is proportional to molecular concentration, as already pointed out. When crystallization commences at a certain number of points in a given volume of liquid the greater the amount of a separating substance in the solution the greater the amount of material crystallized in a given time. Thus crystals of different substances in different concentrations in a rock magma commencing to crystallize at the same time will attain different sizes in like times. The relative sizes of crystals of different minerals are not necessarily indications of different periods or times of growth. Account must be taken of their relative concentrations in the magma.[1]

The size of crystals depends also on the degree of supersaturation taken in conjunction with the molecular concentration, for, as already pointed out, the number of centers of crystallization varies with the degree of supersaturation for a given concentration of a substance, the fewest occurring when crystallization starts near the saturation point in the metastable con-

[1] Pirsson, L. V., Am. Jour. Sci., vol. 7, 1899, pp. 271–280, and Cross, W., Fourteenth Ann. Rep. U. S. Geological Survey, 1905, p. 231.

dition, the greatest number when it starts in a labile condition. The growth of a few crystals in a given volume of solution must lead to larger individuals than the growth of many crystals in the same volume of liquid. If the degree of supersaturation increases during crystallization, by reason of the rate of cooling, the number of crystals may increase from time to time, resulting in different sized crystals of the same substance in some cases; the largest being fewest and the smallest most numerous in most cases.

The size or magnitude of crystals composing rocks may be considered in two ways: one as regards absolute size, the other with respect to relative sizes of the crystals in one rock. The second is connected with the pattern of the rock, or its fabric. The first, or *absolute size* of the crystals in a rock may be considered as strictly its GRANULARITY. When a rock is evenly granular, the crystals nearly all one size, the granularity, or grain, of it is the size of the average-sized crystals. But when a rock is porphyritic, that is, consists of larger crystals in a groundmass, or matrix, of smaller ones there may be two expressions for the size of the crystals: one relating to those composing the groundmass, the other relating to the larger crystals, phenocrysts. In such cases it is customary to express the granularity in terms of the groundmass crystals.

The sizes of crystals in igneous rocks range from those of submicroscopic crystals, indicated only by the exhibition of aggregate polarization, to those of pegmatite crystals which may be measured in meters. The range may be more than 1 : 1,000,000, but it is nearer 1 : 1,000 in the great majority of cases.

**Descriptive Terms Applied to Granularity.** — But little attempt has been made by petrographers to describe the grain of rocks in definite quantitative terms. The commoner terms express certain general ideas of magnitude based on the limit of vision, which naturally varies with individual observers. These are:

PHANEROCRYSTALLINE. — Having all crystals large enough to be seen with the unaided eye; that is, megascopically.

CRYPTOCRYSTALLINE. — When all crystals are too small to be seen with the unaided eye. APHANITIC is a negative term, stating that the rock is not *phaneric*, or is not composed of com-

ponents visible with the unaided eye. It does not state its degree of crystallinity, for aphanitic rocks may be holocrystalline, or they may be partly glassy.

MICROCRYSTALLINE. — When the crystals are only visible with a microscope. This term generally applies to many rocks that are cryptocrystalline.

MICROCRYPTOCRYSTALLINE. — When the crystals are too small to be seen with a microscope, and are recognized as present by the exhibition of aggregate polarization.

MICROAPHANITIC. — When the crystalline character of a microscopic aggregation is in doubt. Such aggregations have sometimes been called MICROFELSITIC. But as this term has been variously defined and used, and is somewhat ambiguous, it is better to replace it by microaphanitic.

The terms *coarse-*, *medium-*, and *fine-grain* are commonly applied to phanerocrystalline rocks without any definite significance. Zirkel has suggested that they be compared with the sizes of peas and millet seed, and this has led to an attempt to give these terms quantitative values as follow:

COARSE-GRAINED rocks, whose average crystals are greater than 5 millimeters in diameter.

MEDIUM-GRAINED rocks, whose crystals are between 5 and 1 millimeter.

FINE-GRAINED rocks, with crystals less than 1 millimeter in diameter.

The grain of rocks may be described more definitely by stating approximately the size of the crystals in terms of the metric system:

*Meter-grained* rocks, having the average size of crystals over one meter.

*Decimeter-grained* rocks, having average-sized crystals from 1 to 10 decimeters.

*Centimeter-grained* rocks, with crystals from 1 to 10 centimeters.

*Millimeter-grained* rocks, with crystals from 1 to 10 millimeters. These include medium-grained rocks and slightly coarse-grained ones.

*Decimillimeter-grained* rocks, whose average-sized crystals are from 0.1 to 1.0 millimeter.

*Micron- (millimillimeter-) grained* rocks, with crystals from 1 to 10 microns, 0.001 to 0.010, millimeters.

Rocks belonging to any one of these divisions have a wide range of variation in size of grain, for the extremes reach a ratio of 1 : 10 for diameters of crystals, which is a ratio of 1 : 100

for areas of crystal sections. Such differences often exist between the phenocrysts and groundmass crystals of porphyritic rocks. The grains of rocks that may be described by any one of the terms just noted are not all of the same order of magnitude, since one may be nine or ten times larger in diameter than another.

**Order of Magnitude of Crystals.** — While it never happens that all the crystals in one rock are the same size, it often happens that they are approximately so, at least so far as concerns the great majority of them. Crystals of approximately the same size may be said to be of the *same order of magnitude.* The latitude of variation permissible in the use of the term "the same order of magnitude" when applied to nearly equidimensional crystals is indicated by the accompanying figures 2, 3, and 4.

Crystals like those in Fig. 2 whose diameters vary within the ratio of 3 : 2 may be said to be of like magnitude, while those with ratios of 2 : 1 or 3 : 1, Figs. 3 and 4, are clearly of differ-

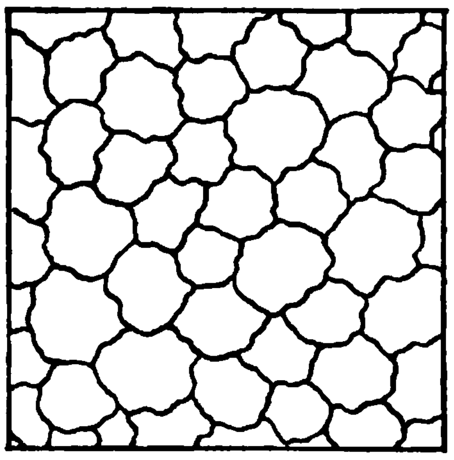


Fig. 2.

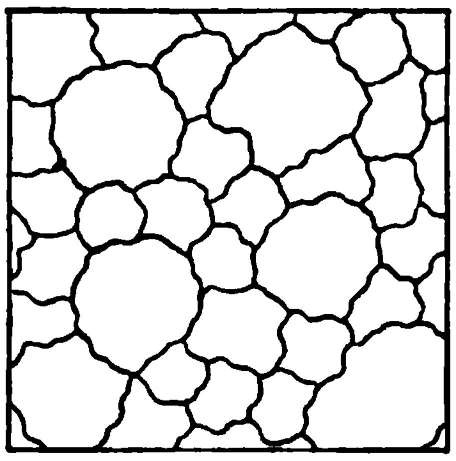


Fig. 3.

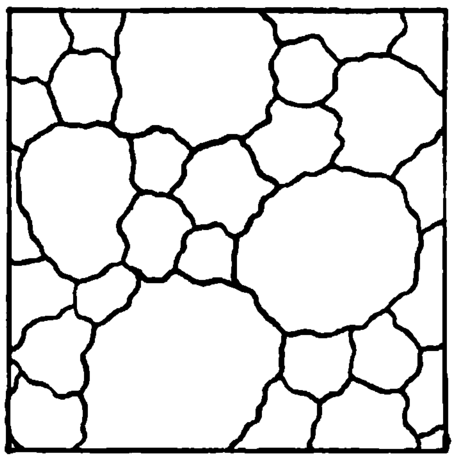


Fig. 4.

ent magnitudes. The areas of crystal sections of like magnitude for the limiting ratio of diameters, 3 : 2, are as 9 : 4 or 2.25 : 1, and the volumes as 27 : 8 or 3.37 : 1. When the crystals of a rock are not equidimensional, but have different shapes, the basis of comparison must naturally be the area of cross sections. Consequently such crystals may be said to have like magnitudes when the areas of the crystal sections are within the limits 2.25 : 1.

## FABRIC

The fabric, or pattern, of a rock as shown on a surface, or in a section, is that factor of its texture which is dependent on the relative sizes of its component crystals, on their shapes and arrangements with respect to one another, and their relative abundance and distribution with respect to a glassy portion of the rock if there is any present. The significance of each of these factors and possible causes for their production will be considered in the order in which they have been mentioned.

**Relative Sizes of Crystals.** — The relation between the size of crystals and the pattern, or fabric, of a rock depends upon the relative sizes of the component crystals and not on their absolute size, for the pattern would be the same if it were enlarged or diminished. As already pointed out, the absolute size may be considered the granularity. Owing to the complexity of most rock fabrics it is advisable to begin with the consideration of somewhat simple, ideal cases in order to emphasize the principles involved in the production and discrimination of those actually developed in igneous rocks.

With regard to the relative sizes of crystals composing a holocrystalline rock it may be said that two groups of cases may be imagined: (1) one in which all the crystals in a rock are the same size, (2) one in which they are different sizes. But absolute identity of size is never realized in fact, so that the idea of like size may be attached to casès in which the crystals are of the same order of magnitude. But even this condition is rarely fulfilled, for it seldom happens that all crystals in an igneous rock are of like order of magnitude, as there are usually present some minerals in small amount and in relatively small sized crystals. So that this group of cases would only be applicable to actual rocks when it is made to include all those of which it may be said that *the size of the great number of crystals that give character to the fabric* of a rock are of the same order of magnitude. Such rocks have been called *equigranular*. The two groups would then be

EQUIGRANULAR fabric, composed chiefly of crystals of like orders of magnitude.

INEQUIGRANULAR fabric, composed chiefly of crystals of different orders of magnitude.

***Equigranular Fabric.*** — Conditions favorable to the production of equigranular fabric must be different for different kinds of magmas. Thus, if the magma consisted of only one component, a uniform rate of crystallization should prevail, either in a metastable condition or in a labile one. Crystallization starting at uniformly distributed points should continue at these centers until the whole magma is solidified. If the magma consisted of two components, then when these are in equal amounts, crystallization should take place at equally spaced points and continue at these centers until solidification of the magma is complete. When the amounts of the two components are not alike, as when one is three times the other, in order that they start to crystallize from equally spaced points in a magma it would seem that they should commence at equal degrees of supersaturation and crystallize at similar rates, or without such increase of supersaturation as would induce separation from new points in the liquid. These conditions probably obtain in eutectic mixtures that have reached the labile stage of supersaturation. For if crystallization begins when the two components are at different degrees of supersaturation, especially in the metastable condition, they will probably crystallize at different rates, and differently sized crystals may result. When the mixture is not eutectic in its proportions, and the rate of crystallization varies for the different components, and takes place from constantly increasing numbers of points, there can be no uniformity in the size of the crystals. The same is true for mixtures of more than two components.

When small amounts of any compounds are present, such as apatite, zircon, allanite, their crystals are usually correspondingly small in size, and they produce little effect on the appearance of the fabric of a rock. They may be considered in such cases as negligible factors in the characterization, or the definition, of the fabric, the more so since they often appear to lie within larger crystals and thus to play the rôle of inclusions.

The use of the term, *equigranular*, or *even grained*, is not commonly so definite as the definition here given would necessitate. It is often applied to rocks that are inequigranular, but in which there is a certain amount of uniformity of appearance due to a regular recurrence of crystals of different sizes in a pattern not sufficiently pronounced as to difference of sizes as to be called porphyritic.

***Inequigranular Fabric.***—Inequigranular fabrics vary greatly in character, or pattern, through gradual transitions from one type to another. Reduced to elemental terms they may be classed as follows:

1. SERIATE, those in which the sizes of crystals vary gradually, or in a continuous series.

2. HIATAL, those in which the sizes are not in continuous series, but in a broken series, with hiatuses, or where two or more sizes are noticeably different from one another.

The latter, being the more distinctive fabrics, have been the first noted and designated by definite names. Seriate fabrics are intermediate in character between hiatal and equigranular.

1. SERIATE fabrics so far as they depend on series of sizes and relative numbers of different sized crystals possess two elements

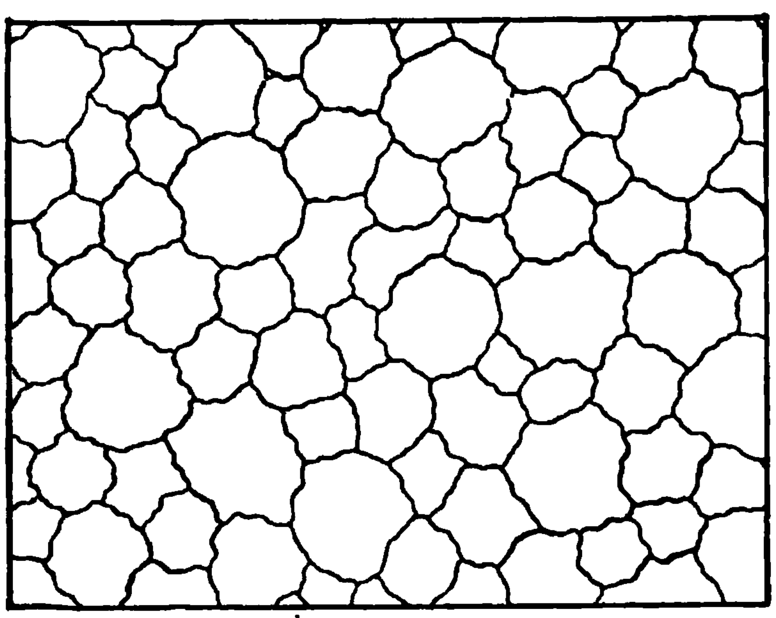


FIG. 5. SERIATE HOMEOID FABRIC.

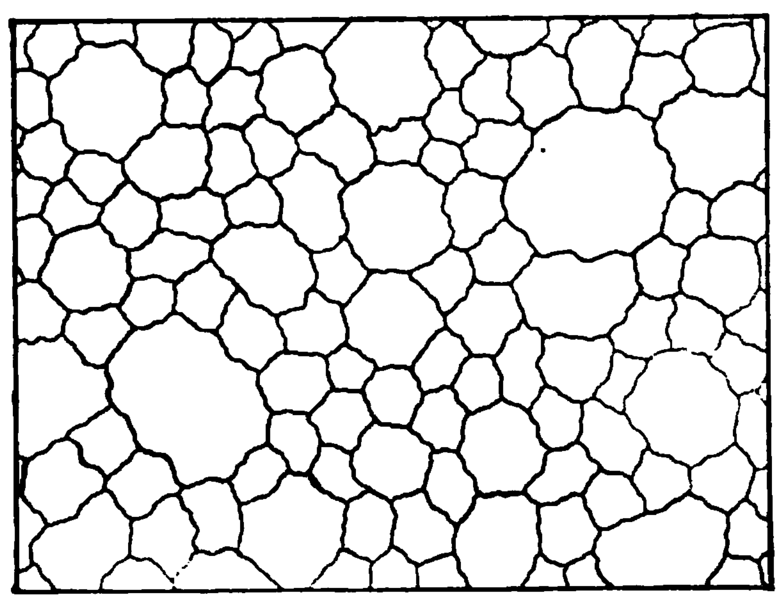


FIG. 6. SERIATE PORPHYROID FABRIC.

of variation, (*a*) ranges in size, between narrow limits, or widely remote limits; and (*b*) ranges in numbers of crystals of each size. Thus (*a′*) the crystals may not be very different in size, possibly within two orders of magnitude. In this case the fabric is not very different from equigranular. Or (*a″*) the crystals may differ greatly in size, the result being a variety of porphyritic fabric. As to the relative abundance of different sized crystals, (*b′*) they may be nearly the same; or (*b″*) they may be quite different, in which case the more numerous are usually the smaller. Examples of these four cases of seriate fabric are shown in Figs. 5, 6, 7 and 8.

The first case, *a′b′*, Fig. 5, with small range of sizes and nearly

equal numbers of different sized crystals may be called SERIATE HOMEOID fabric, owing to its approach to equigranular fabric.

The second, $a'b''$, Fig. 6, with small range of sizes and quite different numbers of different sized crystals may be called SERIATE PORPHYROID fabric, on account of its approach to porphyritic fabric.

The third, $a''b'$, Fig. 7, with wide range of sizes and nearly equal numbers of each sized crystal may be called SERIATE

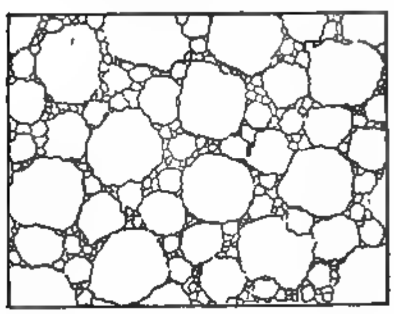


FIG. 7. SERIATE INTERSERTAL FABRIC. FIG. 8. SERIATE PORPHYRITIC FABRIC.

INTERSERTAL fabric, the term intersertal indicating that the interstices between the larger crystals are filled with small ones.

The fourth, $a''b''$, Fig. 8, with wide range of sizes and marked differences in numbers may be called SERIATE PORPHYRITIC fabric.

Conditions favorable to the production of seriate fabric are those which permit the growth of crystals at difiereht rates, or to different sizes, and also from successively increasing numbers of points. Several kinds of cases arise. In one set the crystals may all be of one substance; in others they may be of different substances.

The production of serially different sized crystals of the same compound involves a gradual increase in the degree of supersaturation during the crystallization whereby the numbers of points of separation of solid from liquid steadily increase. The rate of increase may be very slight as in case $a'b'$, Fig. 5, or more rapid as in $a'b''$, Fig. 6. The rate of crystallization in these cases must be relatively slower than in the next two, in which, in case $a''b'$, Fig. 7, the rate of crystallization must have been faster than the rate of increase in supersaturation. In case $a''b''$, Fig. 8, both crystallization and increase in superaturation must be faster than in the preceding cases. Increasing supersaturation in rock magmas goes hand in hand with increase

in viscosity, which induces crystallization of more numerous and smaller crystals.

When more than one substance crystallizes from a magma, the relative amounts, or concentration, of each substance, together with its solubility in the others, affect the rate of crystallization and the size of the crystals. It frequently happens that the large crystals are of one kind of mineral, the small ones of other kinds. A more definite statement may be made in the case of specific igneous rocks.

The cases of seriate fabric so far discussed have been those in which successive growths of crystals are smaller than earlier ones, so that smaller crystals occur outside and adjacent to larger ones. There are cases also in which younger crystals growing larger than older ones inclose the smaller ones. This involves the cessation of crystallization of the older ones before they can be inclosed by the younger. This does not happen with the crystallization of one substance, for when small crystals of any substance are present in a solution they behave as nuclei, upon which more of the same substance will crystallize in continuous parallel crystallographic orientation, even when crystallization is taking place from many new points of separation. So that one never finds small crystals of quartz in various positions surrounded by a larger quartz crystal. The same is true of all other minerals when strict regard is paid to their chemical composition. From the foregoing it is seen that crystals may be in *juxtaposition*, or their relation may be one of *intraposition*. Both kinds of relative positions may occur in one rock.

Most cases of intraposition occur with hiatal fabric, and instances of seriate intrapositions are rare. They must occur when the first substances to separate form small crystals, because they are less soluble and in relatively small amounts, or because they separated with a higher degree of supersaturation, than those substances crystallizing later. The resulting fabric is *seriate poikilitic*, which will be understood when hiatal poikilitic fabric is described.

2. HIATAL fabrics being those in which variations in the sizes of crystals are not in continuous series, but in broken series with hiatuses, it follows that the most characteristic feature of such fabrics is the marked contrast between the sizes of some of the crystals. The most familiar examples of hiatal fabrics are those of *porphyritic* rocks, in which certain larger sized crystals appear

in marked contrast to others that form a groundmass or matrix. Another variety of hiatal fabric is that of *poikilitic* rocks, in which the matrix consists of relatively large crystals carrying smaller crystals as inclusions. These two varieties will be discussed separately.

PORPHYRITIC FABRIC is one in which a GROUNDMASS of crystals or glass carries scattered through it crystals of noticeably larger size. The larger and more apparent crystals are called PHENOCRYSTS. Their actual size may be anything from megascopic to microscopic dimensions. The sizes and the relative proportions between phenocrysts and groundmass constitute the essential quantitative factors of porphyritic fabric.

Relative amounts of phenocrysts and groundmass vary greatly in different cases, from those in which the rock is almost wholly groundmass with very few phenocrysts to rocks in which there is very little groundmass between abundant phenocrysts. Different degrees of abundance may be expressed as in the quantitative system by using the French word pâte = *paste*, for groundmass, and the word semé = *sown*, or sprinkled, for phenocrysts. Five degrees of comparison may be recognized as follows:

PERPATIC, $\frac{\text{g.m.}}{\text{ph.}} > \frac{7}{1}$, extremely rich in groundmass.

DOPATIC, $\frac{\text{g.m.}}{\text{ph.}} < \frac{7}{1} > \frac{5}{3}$, groundmass dominant.

SEMPATIC, $\frac{\text{g.m.}}{\text{ph.}} < \frac{5}{3} > \frac{3}{5}$, groundmass and phenocrysts equal or nearly equal.

DOSEMIC, $\frac{\text{g.m.}}{\text{ph.}} < \frac{3}{5} > \frac{1}{7}$, phenocrysts dominant.

PERSEMIC, $\frac{\text{g.m.}}{\text{ph.}} < \frac{1}{7}$, extremely rich in phenocrysts.

Illustrations of each of these degrees of porphyricity are given in Figs. 9, 10, 11, 12, and 13, in which the proportions of groundmass to phenocrysts are respectively 9 to 1, 4 to 1, 1 to 1, about 3 to 5, and about 1 to 8.

Sizes of phenocrysts may be taken into account in several ways. The crystals may be large enough to be seen megascopically, or they may be microscopic. The first may be called MEGAPHENOCRYSTS, the second MICROPHENOCRYSTS. In the first case the rock may be said to be MEGAPHYRIC; in the second, MICROPHYRIC.

In megaphyric rocks the phenocrysts may be large or small in the same manner that equigranular rocks may be coarse, medium, or fine grained. Adopting similar standards of sizes for mega-

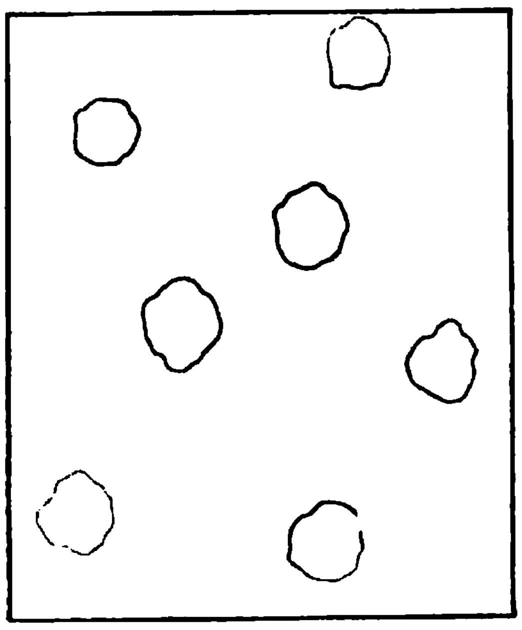


FIG. 9. PERPATIC.

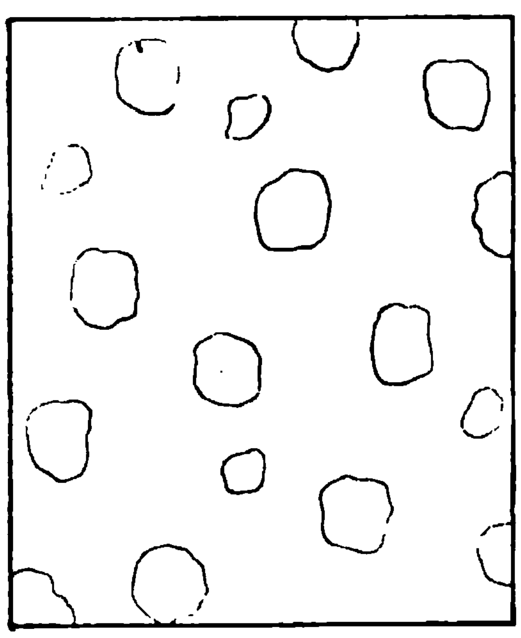


FIG. 10. DOPATIC.

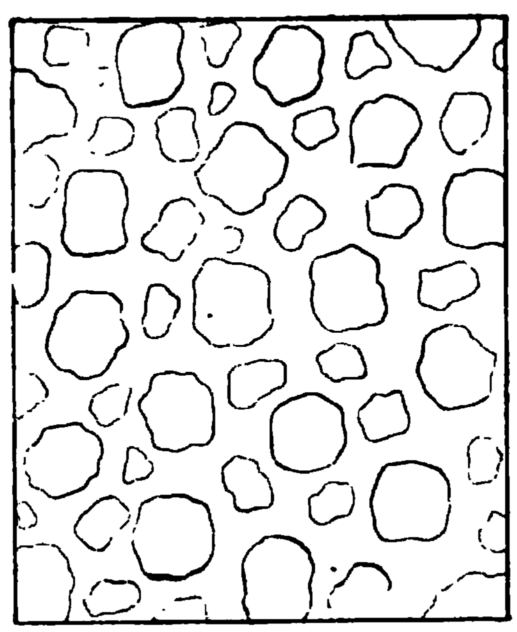


FIG. 11. SEMPATIC.

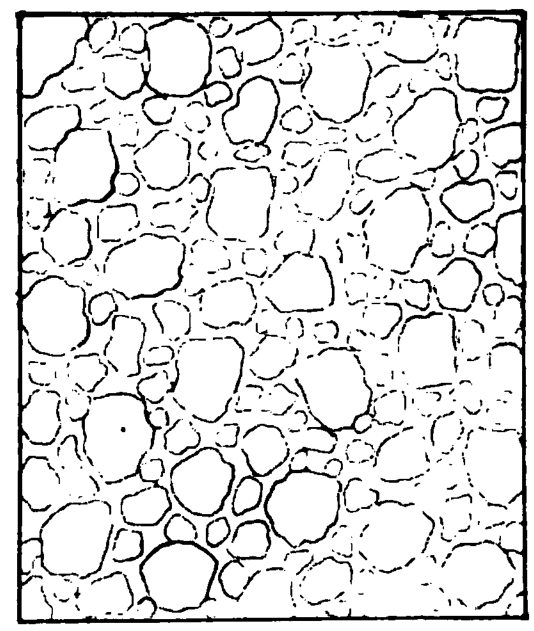


FIG. 12. DOSEMIC.

FIG. 13. PERSEMIC.

phenocrysts as those used to describe coarse-, medium-, and fine-grained rocks, there are:

MAGNOPHYRIC, coarsely porphyritic, rocks, whose phenocrysts are greater than 5 mm. in longest diameter.

MEDIOPHYRIC, moderately porphyritic, rocks, with phenocrysts between 5 mm. and 1 mm. in longest diameter.

MINOPHYRIC, minutely porphyritic, rocks, with phenocrysts whose longest diameters are between 1 mm. and 0.2 mm.

In microphyric rocks corresponding terms for different sized phenocrysts may be employed by changing the *o* to *i*, and reducing the limits of sizes as follows:

*Magniphyric* rocks, with phenocrysts having longest diameters between 0.2 mm. and 0.04 mm.

*Mediiphyric* rocks, with phenocrysts having longest diameters between 0.04 mm. and 0.008 mm.

*Miniphyric* rocks, with phenocrysts having longest diameters less than 0.008 mm.

Such minute phenocrysts are microlites in a groundmass of glass. In fact such microphyric glasses often are groundmasses of megaphyric rocks. And it may be stated in this connection that the groundmass of a porphyritic rock may possess any kind of fabric, including porphyritic.

With regard to the relative sizes of phenocrysts in one rock, they may be all of like order of magnitude, or of different orders of magnitude.

In all of the foregoing varieties of hiatal fabric crystallization might have ceased before the last of the magma solidified to glass without affecting the general character of the pattern. Small portions of glass might fill interstices between rather large crystals, or might be a matrix for innumerable small crystals in a seriate porphyry. Such fabrics are well known in igneous rocks. They may be described as different from holocrystalline varieties, by prefixing the term hyaline to the name of the fabric, as hyaline seriate intersertal fabric, or if it contains less than one-seventh as much glass as crystals it may be described as a percrystalline seriate intersertal fabric.

The groundmass of a porphyry may be of any degree of crystallinity, or of any granularity. It may possess any texture which may characterize a rock as a whole. It may itself be porphyritic. Several general terms have been applied to porphyries to denote the crystallinity of the groundmass:

VITROPHYRE, a porphyry with megascopically glassy groundmass. The texture may be called VITROPHYRIC or VITROPATIC.

FELSOPHYRE, a porphyry with megascopically aphanitic groundmass. The texture would be FELSOPHYRIC or APHANOPHYRIC.

GRANOPHYRE, according to Vogelsang (1867) a porphyry with megascopically granular groundmass. Such a texture would be GRANOPHYRIC or GRANOPATIC. The texture which Rosenbusch has called *granophyric* is here called *graphophyric*, and is described on page 207.

Conditions favorable to the production of hiatal porphyritic fabrics are clearly such as cause sudden changes in the rate of crystallization, and most frequently are sudden changes of temperature, or sudden loss of gases.

Thus in a liquid of one component if crystallization was proceeding in a metastable condition from comparatively few centers, it would require a sudden or very rapid fall in temperature to produce a much higher degree of supersaturation, possibly the labile condition, and to induce crystallization of the same substance from many more points than those at which crystallization was already taking place. It might, however, happen by slower change of temperature if it were sufficiently rapid to raise the supersaturation from the metastable to the labile condition, provided it did not bring about a seriate fabric, as already explained.

If the liquid has more than one component it may happen that one substance is separating in comparatively large crystals in a metastable condition while others remain in solution until they reach a labile condition, when they separate suddenly at innumerable points as comparatively small crystals, forming a groundmass. This is probably the commonest case.

Cases occur in which innumerable small crystals of one or more substances first form in a labile, or highly supersaturated, condition of these substances, and are followed by the production of large crystals, phenocrysts, of another substance which form in a metastable condition. An example is furnished by a porphyry in which microscopic crystals of pyroxene and magnetite constitute much of the groundmass and fill phenocrysts of lime-soda-feldspar as inclusions, but those inclosed in the feldspar phenocrysts are not so large as those in the groundmass, showing that the latter continued to grow after the others stopped because of interference by the growing feldspar phenocrysts.

A porphyritic fabric may also be produced by the larger growth of crystals of those substances which are present in largest amount in the solution, as already pointed out (page 190). So that of several kinds of minerals crystallizing at one time at different points that which is most abundant in solution may form comparatively large crystals which appear as phenocrysts among smaller ones of other minerals.

POIKILITIC fabric is one in which relatively large crystals act as matrix for numerous small ones of other minerals, the smaller crystals lying in all orientations with respect to one another and somewhat uniformly scattered. It is not customary to apply the term to cases in which large crystals contain extremely minute mineral inclusions or to those in which occasional inclusions of considerable size occur irregularly in a larger crystal. The two quantitative factors involved in poikilitic fabric are the relative amounts of matrix crystal and of inclosed crystals and the relative sizes of the inclosed crystals. The matrix crystal, or host, has been called the OIKOCRYST; the inclosed crystals may be called CHADACRYSTS,[1] from χαδ, the

[1] In the paper on "The Texture of Igneous Rocks," these crystals were called xenocrysts, but this term had been used by Sollas previously for crystals inclosed in igneous magmas as the result of partial solution of other rocks.

root of χανδάνω, to hold or contain; that is, crystals contained in the oikocryst, or house-crystal.

All proportions between the amount of oikocryst and of inclosed crystals may exist in different instances. In some cases the matrix crystal constitutes only a slight interstitial cement between the inclosed crystals which then form the great part of the rock. In others the oikocrysts form most of the rock, the chadacrysts being quite subordinate. Relative amounts of the two parts may be expressed by the following fivefold method:

| | | |
|---|---|---|
| PEROIKIC, | $\frac{\text{oikocryst}}{\text{chadacryst}} > \frac{7}{1}$, | oikocryst extremely abundant. |
| DOMOIKIC, | $\frac{\text{oikocryst}}{\text{chadacryst}} < \frac{7}{1} > \frac{5}{3}$, | oikocryst dominant. |
| CHADOIKIC, | $\frac{\text{oikocryst}}{\text{chadacryst}} < \frac{5}{3} > \frac{3}{5}$, | oikocryst and chadacrysts equal or nearly equal. |
| DOCHADIC, | $\frac{\text{oikocryst}}{\text{chadacryst}} < \frac{3}{5} > \frac{1}{7}$, | chadacrysts dominant. |
| PERCHADIC, | $\frac{\text{oikocryst}}{\text{chadacryst}} < \frac{1}{7}$, | chadacrysts extremely abundant. |

The size of the inclosed crystals as compared with that of the matrix crystals may be described as *relatively large, medium,* or *small,* and these expressions may be defined in terms of the average diameters of the chadacrysts and that of the oikocryst.

*Large chadacrysts* are those whose average diameters are greater than one-eighth the average diameter of the oikocryst, Fig. 14.

*Medium-sized chadacrysts* are those whose average diameters are between one-eighth and one-twelfth that of the oikocryst, Fig. 15.

*Small chadacrysts* are those having average diameters less than one-twelfth that of the oikocryst, Fig. 16.

Inclosed crystals may be all of the same order of magnitude, or of different orders. Poikilitic fabric may be megascopic or microscopic. And if it constitutes the whole rock the granularity of the rock should be expressed in terms of the size of the oikocrysts and not of the inclosed crystals.

Conditions favorable to the production of poikilitic fabric are those which permit the separation of all or nearly all the components of a solution but one which crystallizes last, and alone. It cannot be produced from a

liquid of one compound, since the oikocryst and inclosed crystals can never be the same substance, as already explained. The last crystallization does not appear to be a eutectic mixture, but a single substance, simple or complex. Thus quartz may be the matrix for lime-soda-feldspars, almost never for potash-feldspar. Orthoclase may be the matrix for other feldspars and ferromagnesian minerals. Pyroxene may be the matrix for lime-soda-feldspars, and hornblende may be the matrix for lime-soda-feldspars, pyroxenes, and olivine. The separation of these compounds from different

FIG. 14.

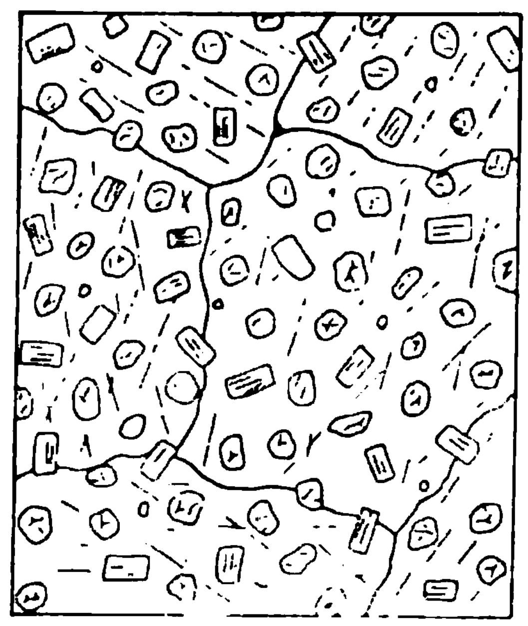


FIG. 15.

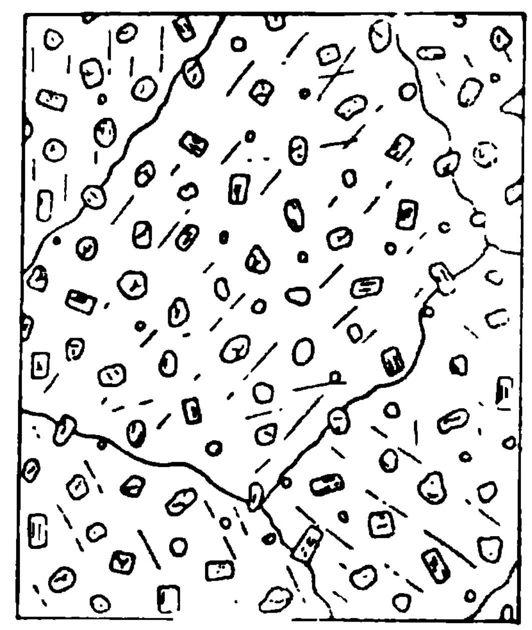


FIG. 16.

solutions leaving one compound in liquid form may be only an apparent case of complete separation of these compounds, for whatever of them may be in the final solution may crystallize upon the surface of the previously separated compounds of the same kind leaving the matrix-forming compound to crystallize in pure crystal. And since the individual oikocrysts are relatively large they must have formed about comparatively few points, and therefore at a low degree of supersaturation. This may have been favored by a lowering of the rate of cooling due to liberation of heat of fusion upon the separation of the earlier crystals, and also to an increase of gaseous components in the remaining liquid due to the solidification of the first part as anhydrous compounds.

**Shapes of Crystals.** — The shapes of crystals are most distinctive features of the fabric of rocks, for it is evident that the character of a mosaic pattern depends largely on the shapes of its component parts, though of course the arrangement of the parts is another important factor. In order to discuss properly the relation between fabric and shapes of crystals it is necessary to consider some of the terms by which the shapes may be described, as well as the significance of the shapes as regards the act of crystallization.

***General Terms.***—The shapes of crystals may be described in terms of their surface features, their bounding surfaces, or their outline in sections, and also in terms of their relative dimensions. In the first instance they may be described in a general manner as possessing crystallographic plane surfaces or not, by such terms as the following:

EUHEDRAL, well faced, completely bounded by crystal planes; equivalent to *automorphic*[1] and *idiomorphic*.[2]

SUBHEDRAL, partially faced, partly bounded by crystal planes; *hypautomorphic*,[1] *hypidiomorphic*.[2]

ANHEDRAL, not faced, without crystal planes; *xenomorphic*,[1] *allotriomorphic*.[2]

In order that a pyrogenetic crystal may develop plane, crystallographic, faces on all sides it must form freely in a liquid without interference. If it grows against another solid, its surface will be conditioned by that of the adjacent solid, and will not be its own, proper, crystal surface. The interfering solid may be a finished, or a growing, crystal, of different mineral or of the same composition. Two crystals of the same kind of mineral may grow against each other and prevent the development of proper crystallographic plane surfaces. They may become subhedral if not interfered with on all sides. If they are so hampered they become anhedral.

But it does not follow that crystals that are not completely bounded by crystal faces have grown against solids, or originally possessed such faces and subsequently lost them, though this may happen in some instances. Nor does it follow that curved, or rounded, surfaces develop only through solution of plane-faced crystals. There may be interference with the regular development of crystal faces and plane surfaces due to irregularities of diffusion of crystallizing molecules and also to the viscosity of the liquid. These will be described more fully later on. With regard to their dimensions the shapes of crystals may be:

EQUANT, equidimensional, or nearly so. More specifically described, they may be cuboidal, polyhedral, spheroidal, or irregularly anhedral.

[1] Rohrbach, Tscher. min. petr. Mitth., vol. 7, p. 18, 1886.
[2] Rosenbusch, Mikro. Phys. Mass. Gest., p. 11, 1887.

Tabular, in plates or tables, when two dimensions are relatively large as compared with the third. Such crystals may be described as plates, tables, disks, folia, scales.

Prismoid, in prisms, when two dimensions are relatively small as compared with the third, or longest dimension. More specifically, prismoid shapes may be described as elongated parallelopipedons, lath-shaped blades, prisms, spindles, fibers.

Irregular, having shapes which cannot be referred to any of the foregoing kinds.

As regards the shapes of crystals composing a rock two general cases may be distinguished:

Equiform, when all or nearly all the crystals have the same shape, as in most rocks composed of one kind of mineral.

Multiform, when the component crystals of a rock have different shapes, which is the usual case when there are several kinds of minerals present.

***Shapes of Specific Minerals.*** — The shapes of crystals in igneous rocks are closely related to the habits of the particular mineral crystal as it develops under different conditions of viscosity of the liquid magma and under different environment of other crystals. This relationship will be pointed out for the principal pyrogenetic minerals, since the shapes of the preponderant crystals give character to the fabric of rocks.

Quartz commonly crystallizes from igneous magmas in nearly equidimensional crystals, which when euhedral are bounded by plus and minus unit rhombohedrons resembling hexagonal bipyramids, Fig. 17. Sometimes with very short hexagonal prism faces of the first order $(10\bar{1}0)$. In rare instances quartz phenocrysts in some porphyries have a prismatic habit, but the prisms are short in these cases. Sections of quartz crystals are commonly hexagonal or nearly square rhombs, Fig. 18. Subhedral and anhedral crystals may then be nearly equidimensional or equant, Fig. 19. But irregularly shaped outlines are common owing to interference by adjacent crystals and to embayments of magma which must have been quite viscous when partially inclosed by the quartz, Fig. 21, p. 332.

Equant crystals of quartz form not only under conditions permitting the growth of large phenocrysts and small ones, but also under those that cause the production of minute,

microscopic crystals in rock glasses, obsidian. They appear to develop under conditions of different viscosity of the magma and of different rates of cooling. They are found in coarse-grained holocrystalline rocks, and in highly glassy ones, as just said. Very commonly, then, abundant quartz in an igneous

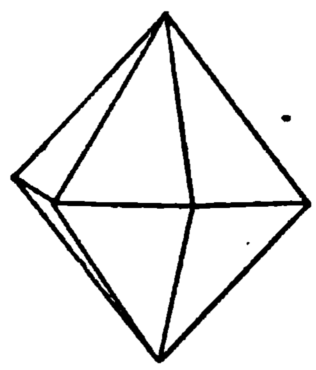


FIG. 17.

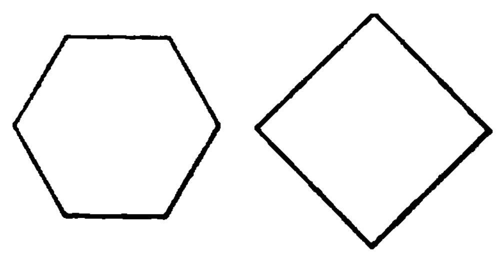


FIG. 18.

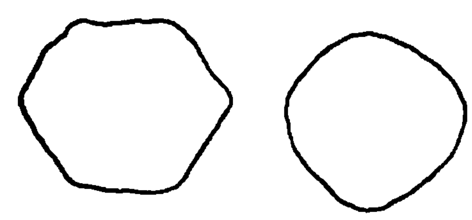


FIG. 19.

rock leads to abundant equant crystals affecting to a greater or less extent the fabric.

When, however, quartz crystallizes at the same time with other minerals in a metastable state, especially when it is crystallizing about a nucleal crystal, it may form irregularly anhedral or subhedral crystals that are intergrown with whatever other mineral is separating at the same time and in the same spot in the magma. The commonest mineral with which quartz may intergrow in this manner is potash-feldspar, less often sodic feldspars, and still less frequently ferromagnesian minerals, such as garnet, tourmaline, mica, etc. Owing to the peculiar pattern exhibited by some quartzes in feldspars, which suggests cuniform inscriptions, dominant lines intersecting at 60 degrees, this intergrowth has been called GRAPHIC, Fig. 20, resulting in GRAPHIC FABRIC. It has also been called pegmatitic, and when very fine-grained, usually microscopic, it has been called granophyric. But these terms are less appropriate and have connotive significances which are objectionable, and should be avoided for this mode of intergrowth. When microscopic, the fabric is MICROGRAPHIC. In section it assumes many types of shapes, one of which is shown in Fig. 21.

In general the form of the quartzes is anhedral, often curved and rounded, and usually elongated, rodlike, or prismoid. However, the axis of the prismoids is not the crystallographic prism axis, *c*, but appears to be determined by the direction in which quartz material reached the growing crystal. This is shown by Fig. 22, representing a section of feldspar and

Fig. 20. Graphic Fabric (Merrill, National Museum).

Fig. 21. Micrographic Fabric (Merrill, National Museum).

intergrown quartz from a porphyry from Eureka, Nev.[1] In this, which is typical of many cases, it appears that the direction of the quartz rods, or prismoids, is normal to surfaces of the feldspar crystal, and the direction of the *c* axis in the quartz is inclined to the long axis of the prismoids.

A distinguishing feature of graphic intergrowths is that neighboring quartz prismoids have exactly the same crystallographic molecular orientation which is shown by the optical parallelism of neighboring quartzes. This must result from actual connection of all such parts with one another, or from some orienting influence exerted on the apparently disconnected

Fig. 22. Graphic Intergrowth of Quartz and Feldspar.

crystals by the inclosing crystal, or there must be some orienting influence extending from one crystal of quartz to another through an appreciable distance in the liquid magma. All such parallelly oriented crystals may be looked upon as a single crystal individual, which, if the intervening, inclosing, feldspar were removed, would appear as a more or less branching, coral-like structure, not made up of aggregated crystals, but as a single crystal intricately carved out. It is not certain, however, that all parallelly oriented parts are actually connected with each other. And it is certain that there is no fixed crystallographic relation between the quartz and the inclosing feldspars, for one crystal of feldspar in some instances contains more than one group of quartzes, and no constant relation of positions of the two minerals has been observed.

[1] Mon. 20, U. S. Geological Survey, App. B, 1892, p. 375.

The frequent occurrence of curved, or rounded, shapes of quartz crystals in graphic fabrics and the similar rounded shapes of crystals of metals in alloys with like graphic (eutectic) fabric is to be noted as well established examples of rounded crystals that have grown with such forms in the first instance, and have not grown as euhedral crystals that afterwards became round by solution in the magma before its complete solidification.

The development of graphic fabric upon the simultaneous crystallization of the components of eutectic mixtures in alloys[1] has led to the name of eutectic fabric, and to the assumption that graphic fabric is an indication of the simultaneous crystallization of components in eutectic proportions in rock magmas. It certainly is an indication of simultaneous crystallization, but so is also the mutual interference of adjacent anhedral crystals. And such a granular fabric frequently results from the solidification of eutectic mixtures, as noted by Miers,[2] Day and Wright,[3] and as observed in igneous rocks; for rocks having the same composition as those with graphic fabric often have consertal granular fabric.

The most irregular shape assumed by quartz crystals is that resulting from the inclosure of numerous other smaller crystals by a quartz crystal. In this case quartz plays the rôle of matrix or oikocryst in poikilitic fabric which is oftenest microscopic, and may be developed in the groundmass of a porphyry, or in larger pattern in quartzose phanerocrystalline rocks, where there may be suggestions of earlier euhedral forms subsequently extended by the further separation of quartz from the liquid magma upon the complete solidification of the liquid, Fig. 23.

When quartz crystals grow on the walls of cavities in igneous rocks as the first crystallizations from vapors that were in solution in the magma they usually develop distinct crystallographic faces, and may assume pronounced prismatic shapes.

[1] For works on alloys see Siderology, The Constitution of Iron Alloys and Slags, H. F. v. Jüptner, translated by Chas. Salter, London, 1902, and Introduction to Metallography, by Paul Goerens, translated by Fred Ibbetson, 1908.

[2] Miers, H. A., and Isaac, F. Proc. Royal Soc. A., vol. 79, 1907, pp. 349–350.

[3] Day, Shepherd, and Wright, Am. Jour. Sci., vol. 22, 1906, p. 289, and Allen, White, Wright, and Larsen, *ibid.*, vol. 27, 1909, pp. 1–47.

Such cavities may form in phanerocrystalline rocks upon the contraction of the last of the magma in passing from liquid to solid crystal phase, and when uniformly distributed through a rock produce what is known as MIAROLITIC texture, such cavities also being called *miarolitic.*

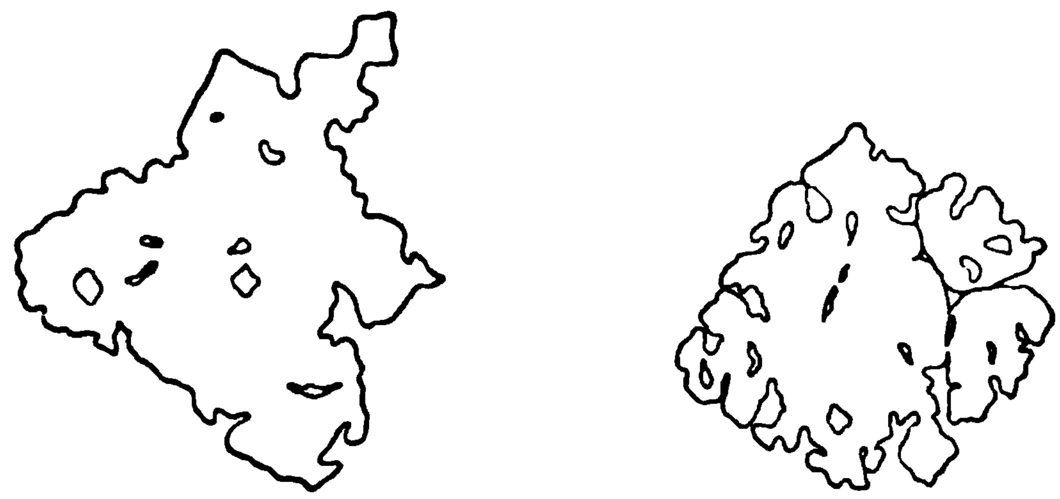


FIG. 23.

The large cavities often developed in pegmatites and usually distributed very irregularly through the rock are of the same character as miarolitic cavities in finer grained rocks. Pyrogenetic cavities form in certain porous, or partly hollow, spherulites and lithophysæ. And the quartz crystals in hollow spherulites in highly siliceous lava (rhyolite) at Glade Creek, Yellowstone National Park,[1] which are comparatively large and are prismatic, have, besides dominant prism planes $(10\bar{1}0)$ and the unit rhombohedron $(10\bar{1}1)$, subordinate planes of $(30\bar{3}2)$, $(03\bar{3}2)$, and trapezohedrons $(12\bar{3}2)$.

Since there is a transition point in quartz at 570°, at which it passes from hexagonal trapezohedral symmetry above this temperature to trigonal trapezohedral symmetry below it, and the transition from higher to lower symmetry is usually accompanied by the development of twinning in irregularly bounded spaces, it is often possible to determine whether quartz crystals were formed above or below 570°. The observations of Wright and Larsen show that the quartzes in granites were formed above 570°, and much of the quartz in pegmatites also, certainly that graphically intergrown with feldspar, whereas the quartz in cavities, so far as studied, was formed below 570°; indicating that pneumatolytic processes usually take place at temperatures below 570°.

The formation of crystals in gases in igneous rocks has been called a pneumatolytic process by Rosenbusch, but there may be actions of this kind in which the gases are those dissolved in the magma and the crytallization may take place with the cooling of the magma; and there may be cases in which gases from some distant source attack previously solidified magmas.

[1] Iddings and Penfield, Am. Jour. Sci., vol. 42, 1891, pp. 39–46.

Both of these kinds of processes may be called pneumatolytic. The first may be considered as primary, the second kind as secondary.

TRIDYMITE crystallizes in thin plates with hexagonal outline, which may form aggregates of microscopic individuals, which are anhedral to subhedral and in section are nearly equidimensional, or equant. Such aggregates have been described as like roofing tiles in section, and are usually very small and insignificant. When it crystallizes in the presence of more gas, generally within cavities, or associated with cavities, tridymite forms larger plates twinned at such an acute angle that the plates wedge out against one another, or they group themselves in spherical aggregates, seldom more than a millimeter in diameter. Tridymite occurs in these various forms in some lavas, usually in such small amounts that it does not give special character to the texture.

FELDSPARS separate from igneous magmas in crystals having different shapes or habits in different cases. They may all of them be equant in some rocks, tabular in others, and prismoid in others. Or they may possess different shapes in one rock according to the conditions under which they were formed. Frequently feldspar phenocrysts have quite a different habit from the feldspars forming the groundmass. Owing to the fact that potash-feldspar does not form with albite and the lime-soda-feldspars homogeneous crystals in all proportions under the conditions attending the solidification of rock magmas, it is better to consider the shapes of crystals of potash-feldspar and those of crystals of the lime-soda-feldspars separately, although there are many analogies and resemblances between them.

POTASH-FELDSPAR, orthoclase and sanidine, forms euhedral crystals bounded by the second and third pinacoids (010), (001), two pinacoids of the third kind (110), ($1\bar{1}0$), commonly called the prism ($m$), and generally one or two pinacoids of the second kind, $x$ ($\bar{1}01$) and $y$ ($\bar{2}01$); sometimes subordinate planes $o$ ($\bar{1}11$) and $o'$ ($\bar{1}\bar{1}1$), Fig. 24; besides occasionally other planes. Such crystals may be nearly equidimensional or equant, Fig. 24, or tabular parallel to the second pinacoid (010), Fig. 25. In rarer instances, as when the crystals form in the presence of gases in cavities, as at Obsidian Cliff, Yellowstone National Park, they may be tabular parallel to (001), Fig. 26. This habit has not been observed on crystals formed within the magma. Prismatic shapes are produced by the elongation of crystals in the

direction of the *a* axis, Fig. 27, and in certain rarer instances parallel to the *c* axis, Fig. 28. Branching crystals elongated in both these directions form in some glassy rocks, Fig. 29. The shapes are further modified by twinning; Carlsbad twin-

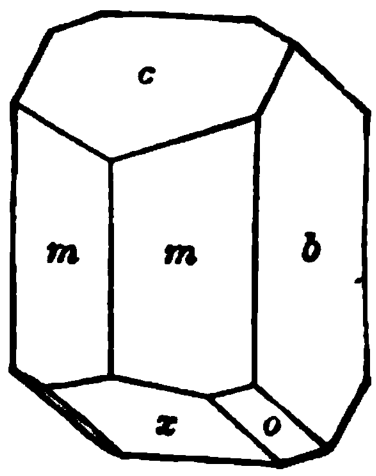



FIG. 24.

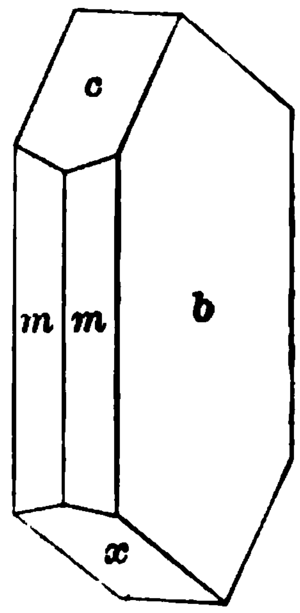



FIG. 25.

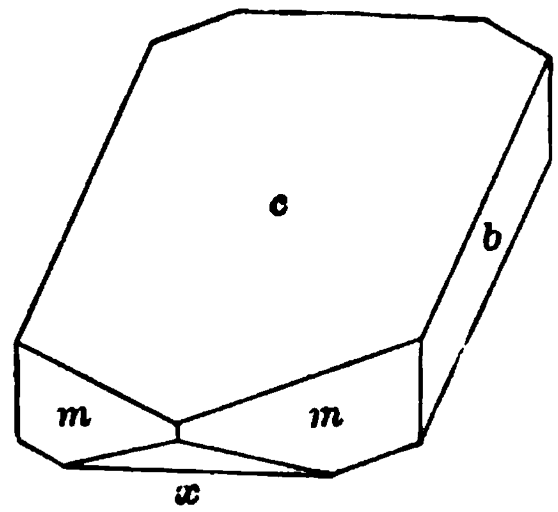



FIG. 26.

ning occurring in equant crystals and in those tabular parallel to (010), or prismatic in the direction of the *c* axis. Baveno twinning occurs in crystals prismatic in the direction of the *a* axis. And Manebach twinning occurs in prismatic crystals

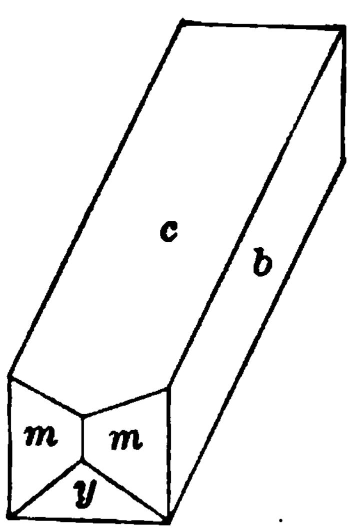



FIG. 27.

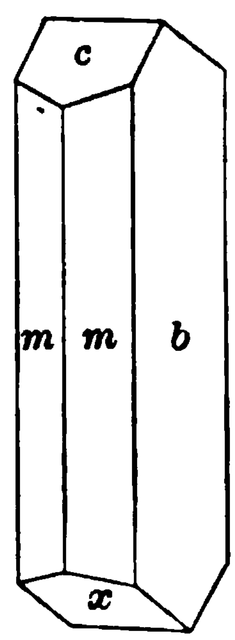



FIG. 28.

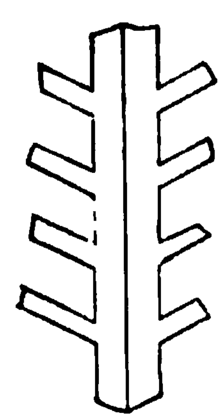


FIG. 29.

elongated parallel to the *a* axis and in tabular crystals flattened parallel to the third pinacoid (001).

*Equant* crystals of potash-feldspar are euhedral when they occur as phenocrysts in some porphyries, indicating an approximately uniform growth in all directions, resulting from ease of diffusion or gradual, comparatively slow, crystallization, since

the most tabular and prismoid crystals form rapidly and also in highly viscous magmas. Equant crystals of orthoclase are anhedral when they form at the same time in juxtaposition with equant crystals of other minerals, such as quartz. This may be a rapid crystallization in a labile condition as Miers has shown for certain eutectic mixtures. Or they may form almost by themselves without regard to the presence of crystals of other minerals. There may thus be developed an equant granular fabric produced in the main by crystals of orthoclase. But this fabric is more frequently produced when equant quartzes are also present. Equant anhedrons of orthoclase may be of any size from rather large megascopic crystals to minute, microscopic ones.

*Tabular* crystals of potash-feldspar may be euhedral when they form phenocrysts in some porphyries, using this term in its broadest sense. That is, they may be megascopic phenocrysts, or microscopic crystals in a glass matrix, more commonly called microlites. But the larger the crystal, in general, the less pronounced the tabular character. Thus megascopic tabular phenocrysts of orthoclase are rarely more than three times as broad as they are thick, whereas microscopic plates may be more than thirty or forty times as broad as thick. The tabular character becomes highly developed in crystals that form in rapidly cooling, highly viscous magmas. Extremely thin plates of orthoclase often form in the groundmass of porphyries rich in this compound, when the phenocrysts of orthoclase are more or less equant. Anhedral tabular crystals are oftenest produced when a magma consists chiefly of potash-feldspar and rapidly crystallizes into small individuals. They are seldom developed in coarsely crystallized rocks.

*Prismoid* crystals of potash-feldspar may be euhedral when phenocrysts, either megascopic or microscopic, that is, microlites in glass. It is true in this case also that the larger the crystals the less pronounced the prismoid habit, megascopic crystals being usually relatively thick, short prisms, whereas microscopic ones may in some cases be extremely thin, long, needle-like crystals. Evidently the latter develop readily in highly viscous magmas. Moreover, it happens that prismoidal orthoclases oftener form in the more siliceous magmas, and are accompanied by quartz

or tridymite; while tabular orthoclases more frequently form in less siliceous magmas rich in potash-feldspar, and, therefore, are seldom associated with notable amounts of quartz. Special types of prismoid orthoclase will be described in connection with the arrangement of crystals.

Soda-potash-feldspars crystallize in the same forms as potash-feldspar, and are not generally distinguishable by means of their shapes. The unstriated, alkali-feldspars in many igneous rocks contain notable amounts of sodium. This is true of the feldspars in the obsidian of Obsidian Cliff, Yellowstone National Park, which furnish the illustrations for numerous varieties of shapes represented by the figures. When, however, the sodium exceeds the potassium considerably, so that the feldspar is

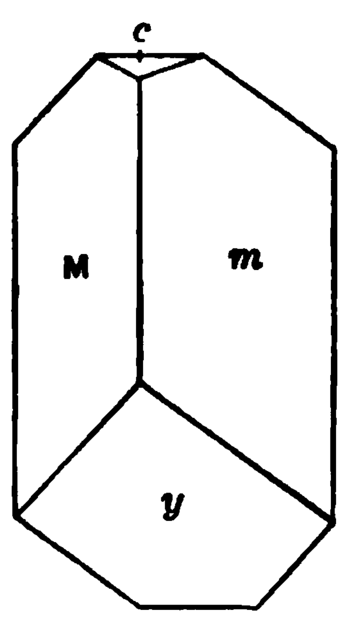



Fig. 30.

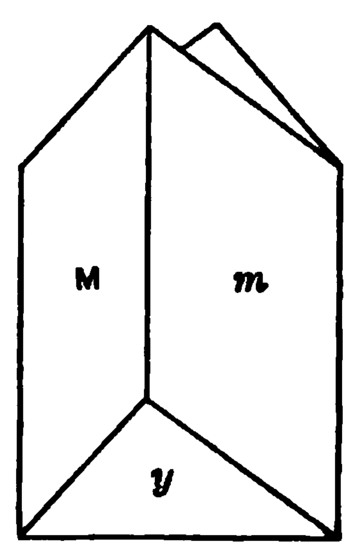



Fig. 31.

properly a potash-soda-feldspar, which may in some cases contain a small amount of calcium ($Or_{2 \cdot 1}Ab_4An_1$, Kilimanjaro, Africa), a special type of crystal is sometimes formed, such as the megascopic phenocrysts in certain porphyries of Norway, rhombenporphyries. This is shown in Fig. 30, which is a flat rhombic prism, wedge-shaped at the ends, and sometimes twinned, and grown together on the first pinacoid (100), Fig. 31. Subhedral and anhedral crystals of this type also occur in certain coarsely grained rocks in Norway, rich in potash-soda-feldspars, soda-microclines.

Lime-soda-feldspars, including all proportions of albite and anorthite, may crystallize in very similar shapes, but there are differences in the habit according to the conditions under which they crystallize. And since the chief factor affecting their habit

appears to be the viscosity of the liquid from which they separate, and as the more calcic feldspars form the more fluid liquids when melted, and are seldom associated with potash-feldspar and quartz, both of which are highly viscous when liquid, it follows that the more calcic the feldspar the more likely its crystals are to be equant, or nearly so, for a given set of attendant conditions. The relation between habit and viscosity is well illustrated by the shapes of some microscopic crystals of lime-soda-feldspar which have formed in cooling liquids of the feldspar made in the laboratory.[1]

In the case of labradorite-andesine ($Ab_3An_1$) there are minute nearly equant to thick tabular or bladed crystals that extend into longer bladed forms much thinner at the margins than at the center, Fig. 32, and other

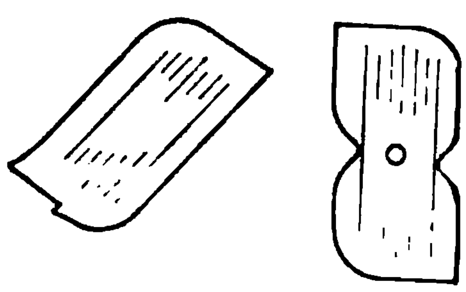


FIG. 32.

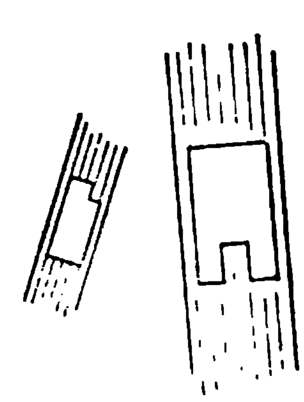


FIG. 33.

crystals that are equant to thick tabular or thick prismoid forms that pass into extremely thin hair-like prisms, Fig. 33. This is a well-known phenomenon in some glassy igneous rocks, and shows that when the crystal began to form it was able to grow at nearly equal rates in three directions, but as cooling progressed and the surrounding liquid became more viscous, thin tabular and finally extremely thin prismatic shapes are assumed by the growing crystal, which is chemically homogeneous. For there are cases where it can be demonstrated that the optical orientation, and, therefore, the chemical composition, is constant in all parts of the crystal.

When zonal structure is developed by changes in the composition of the feldspar, the first, or central, part of the crystal being more calcic than the margin, there must be a change in the composition of the liquid whereby the composition gradually becomes poorer in anorthite and relatively richer in albite. There should then be an increase in the viscosity of the liquid independent of any increase due to lowering of temperature, which acts in the

[1] The Isomorphism and Thermal Properties of the Feldspars. Day, Allen, Iddings. Carnegie Institution of Washington, 1905, p. 91.

same direction. It is commonly observed that the inner zones, or cores, of a zonally built feldspar are more nearly equant than the outer zones, or the final shape, of the crystal.

Euhedral crystals of lime-soda-feldspars often are bounded by nearly the same planes as those on orthoclase *b* (010), *c* (001), *m* (110), *M* ($1\bar{1}0$), *x* ($\bar{1}01$) and *y* ($\bar{2}01$), and sometimes others.

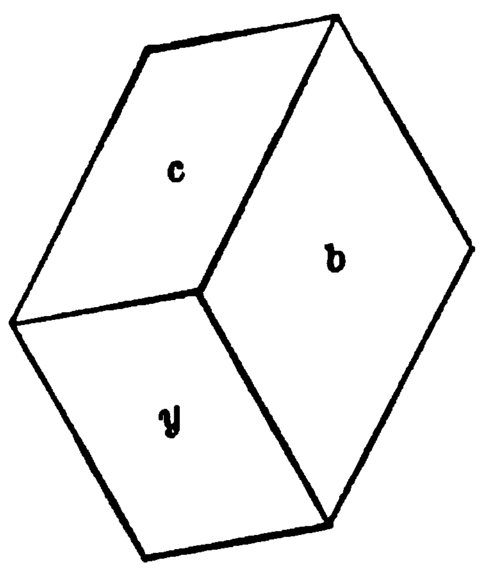



FIG. 34.

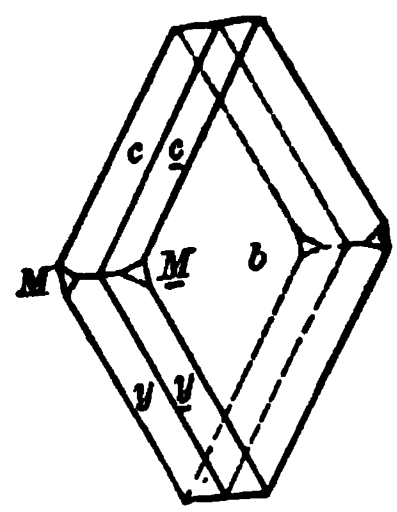



FIG. 35.

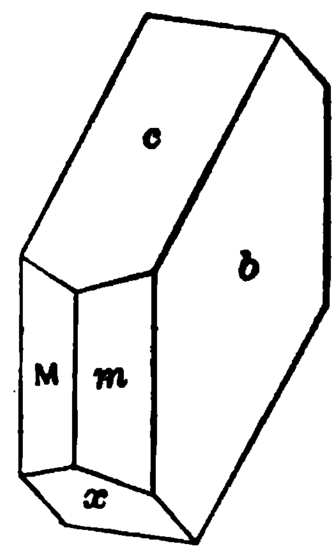



FIG. 36.

But euhedral crystals are less common than with orthoclase. In some cases the pinacoids *c* (001), *y* ($\bar{2}01$), and *b* (010) dominate, and the crystals have nearly cuboidal shapes, as is the case with anorthite from lava from Miakijima, Japan, Fig. 34. When such

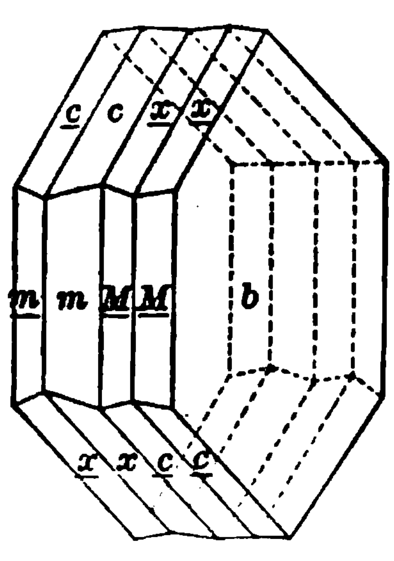



FIG. 37.

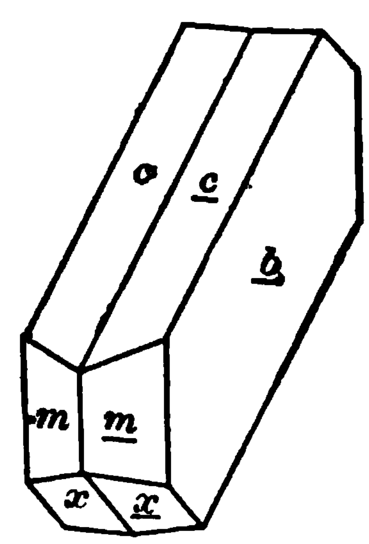



FIG. 38.

crystals are tabular parallel to *b* (010) they form nearly square plates, Fig. 35. Tabular crystals also occur similar to those of orthoclase, Fig. 36, and may be Carlsbad twins of albite twins, Fig. 37. They may also be twinned according to the pericline law. Prismoid crystals are elongated in some cases in the direction of the *c* axis; in others parallel to the *a* axis, Fig. 38. This

is more commonly the habit of microscopic prismoid crystals, which are twinned according to the albite law.

*Equant* crystals of lime-soda-feldspar are euhedral when they are phenocrysts in porphyritic rocks, oftenest when megascopic, seldom as microscopic ones in rock glasses. Equant crystals of these feldspars are anhedral in certain equigranular rocks composed largely of feldspar, anorthosites and some gabbros, or of the highly sodic feldspars and quartz, albite-granites. These rocks are oftenest coarse-grained, though fine-grained and aphanitic varieties are known with equant anhedral lime-soda-feldspars.

*Tabular* crystals of lime-soda-feldspar may be euhedral when phenocrysts, large and small, and when they are the chadacrysts in that variety of poikilitic fabric called *ophitic*. As anhedral crystals they occur occasionally in coarse-grained rocks almost wholly feldspar, as in anorthosite, in the Wachita Mountains, Oklahoma, also in finer-grained rocks. They form as microscopic plates in the cooling of melted feldspar in the laboratory.

*Prismoid* crystals of these feldspars are euhedral when phenocrysts of all sizes, and, perhaps, are more commonly developed than equant or tabular shapes. They are specially frequent as small and as microscopic crystals; and the smaller the crystal the more pronounced the prismatic habit. Prismoid crystals of lime-soda-feldspars, whether euhedral or anhedral, are more often developed the more viscous the liquid from which they crystallize, as already said, and as the more alkalic feldspars yield the more viscous liquids they are oftener developed in prismoid shapes than the more calcic feldspars. That is, albite and oligoclase when in microscopic crystals usually form relatively thinner, longer prismoids than labradorite and anorthite. The latter oftener form stout rectangular prismoids, which in section are generally described as "lath-shaped."

NEPHELITE crystallizes in hexagonal prisms with the basal pinacoid, seldom modified by other planes. The habit is nearly equant in some instances, when the prisms are nearly as broad as they are long. It is sometimes tabular, in relatively thick plates parallel to the basal pinacoid. It is in some cases prismoid, in stout prisms, almost never in slender, long prisms. Euhedral crystals occur as phenocrysts of various sizes,

Anhedral ones are not specially characteristic of any particular mode of solidification of a nephelite-bearing magma, but irregular shaped, rounded prismoids occur as graphic intergrowths of nephelite in alkalic feldspar in some phanerocrystalline rocks, nephelite-syenites. Their common shape is equant, and the presence of abundant crystals of nephelite tends to produce a fabric characterized by crystals of equant shapes.

LEUCITE and the SODALITE minerals, since they crystallize in the isometric system, form equant crystals that are rarely euhedral, oftener subhedral and anhedral. The same is true of *garnet* and *magnetite*, which seldom are present in such amounts as to control the character of the fabric of igneous rocks.

MICAS commonly crystallize in tabular shapes, flattened parallel to the third pinacoid *c* (001). Crystals vary considerably in thickness, larger ones being generally relatively thicker than smaller ones, which when microscopic are often extremely thin as compared with their breadth. Large crystals are sometimes nearly equant, that is, as thick as broad. Less often they are prismoid in the direction of the *c* axis, that is, nearly perpendicular to the cleavage plane. In rare instances mica crystals are elongated in the plane of cleavage parallel to the *a* axis. Euhedral crystals occur as phenocrysts and as microscopic crystals in rock glass. Subhedral and anhedral crystals of irregular outline occur in rocks of various granularity and fabric. Occasionally mica is graphically intergrown with quartz, usually at one end or side of a mica crystal. The shapes of the mica parts of the intergrowth are quite irregular.

PYROXENES crystallize from igneous magmas in equant or prismoid shapes, almost never in distinctly tabular forms, though crystals are sometimes flattened in one of the two pinacoids *b* (010) or *a* (100). Euhedral crystals of monoclinic pyroxene are commonly bounded by the planes shown in Figs. 39 and 40, *a* (100), *b* (010), *m* ($1\bar{1}0$), *s* (111); less frequently other planes. In the sodic varieties, ægirite-acmite, the pinacoid *b* (010) is generally absent, and there are sometimes steep terminal planes. The characteristic difference between the sodic pyroxenes and other varieties is shown in Figs. 41 and 42; the first a cross-section of ordinary pyroxenes; the second one of ægirite. Euhedral crystals occur as phenocrysts of all sizes,

equant, flattened, or prismoid; and subhedral crystals with distinct planes in the zone of the *c* axis, but without definite crystallographic planes terminating the prisms, also occur in this manner, being more common than euhedral ones. Anhedral

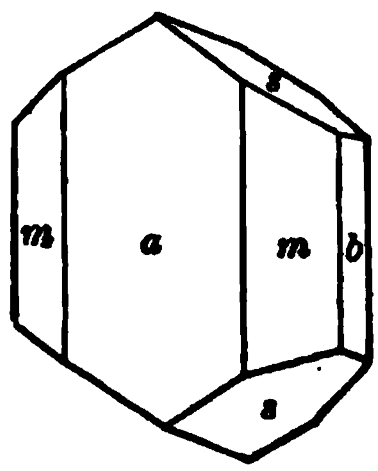



FIG. 39.

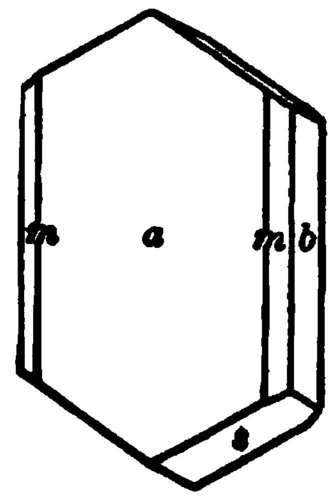



FIG. 40.

crystals, equant or prismoid, develop in rocks of various granularities and fabrics. In general, however, equant crystals are more commonly formed under conditions producing larger crystals than under those producing microscopic ones. Evidently the more viscous the magma the more prismoid the

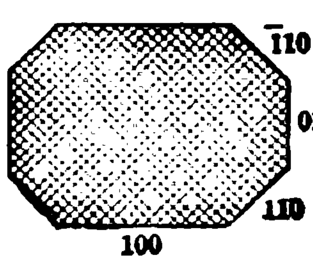



FIG. 41.

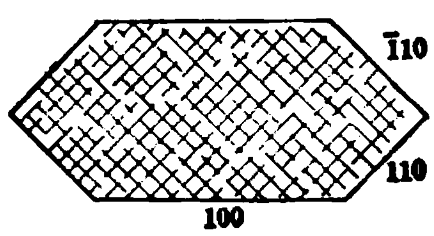



FIG. 42.

crystals of pyroxene. There is a relation between the habit of the crystals and their composition, which may be a function of viscosity also. It is that the more sodic pyroxenes, ægirite-acmite, are oftener prismoid than the less sodic ones, and the prisms are relatively longer and more slender. There seems to be no characteristic difference in habit between crystals of monoclinic, calcic pyroxenes, diopside, augite, and those of the orthorhombic pyroxenes, enstatite, hypersthene.

AMPHIBOLES crystallize very similarly to pyroxenes so far as habit of crystals is concerned. Equant and prismoid shapes are common; tabular ones almost never develop in igneous magmas. Euhedral crystals have the simple forms shown in Fig. 43, rarely other planes. Subhedral crystals definitely

bounded in the zone of the *c* axis and irregularly terminated are common. Euhedral crystals occur chiefly as phenocrysts, large or small; that is, including microscopic crystals in a glass matrix. The larger crystals are oftener equant, the smaller ones prismoid. In general, amphiboles form more pronounced prismoids than pyroxenes under what appear to be like conditions of formation. Amphibole crystals are oftener longer and more slender than those of pyroxenes, other than ægirite-acmite. However, the very characteristic acicular crystals of tremolite and actinolite are not pyrogenetic in igneous rocks, but are the

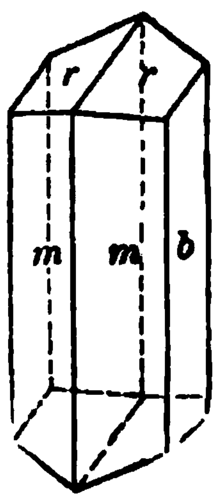



FIG. 43.

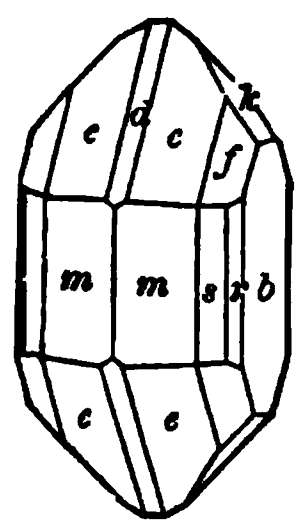



FIG. 44.

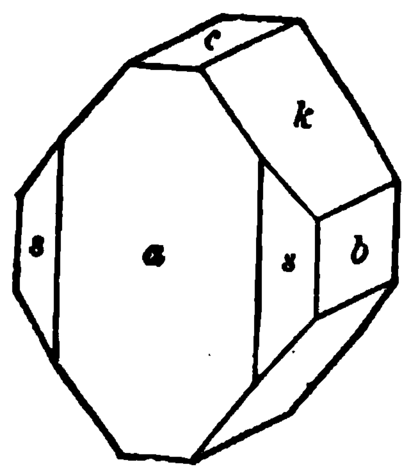



FIG. 45.

product of secondary actions. Moreover, amphibole is less often crystallized from rapidly cooling magmas than pyroxene is, so that highly attenuated prisms, needle-like, or even hair-like, in shape, are more commonly formed of pyroxene than of amphibole.

OLIVINE crystallizes from igneous magmas generally in equant or nearly equant shapes, almost never distinctly tabular, and rarely prismoid. The forms usually developed on euhedral crystals are shown in Figs. 44 and 45, *a* (100), *b* (010), *c* (001), *k* (021), *m* (110), *s* (120), *r* (130), *d* (101), *e* (111), *f* (121). Crystals may be flattened somewhat parallel to *a* (100) or *b* (010). When prismoid, the elongation is in the direction of the *c* axis. Euhedral and subhedral crystals occur as phenocrysts, megascopic or microscopic. In rare instances prismoid anhedral crystals have developed which are long and slender, and may also be irregularly shaped, as in basaltic lava, in the Hawaiian Islands, Fig. 46.

Other minerals, as apatite, titanite, tourmaline, have distinctive

shapes as pyrogenetic crystals, equant, tabular, and prismatic, and when present in considerable amounts lend noticeable character to the fabric of the rock, but their amounts are usually so slight that they seldom affect the fabric appreciably. In specific cases their part in the fabric may be pointed out, but there is no need of considering them in detail in this place.

FIG. 46.

**Arrangement of Crystals.** — The arrangement of crystals in a rock is a most important factor of its fabric, and may be discussed in a general manner for most rocks, and also in a specific way for certain very characteristic cases. Considering first those cases in which the crystals are mostly the same shapes in one rock, and are also of like magnitudes, it is evident that the results of different kinds of arrangements will vary with the shape of the crystals.

***Arrangement in Equigranular Rocks.*** — EQUANT. — When nearly all the crystals are equant, there can be no variation in the arrangement of them, considered merely as shapes, for they must lie in juxtaposition and produce a uniform pattern. If the crystals were of several kinds of minerals and of different colors, various arrangements of the differently colored crystals would produce variations in fabric as regards color, that is, various color patterns. It would be proper to describe the fabric in terms of the shapes of the crystals as equiform and equant, and in addition describe the arrangement of the different kinds of minerals.

TABULAR crystals may be arranged in the following general ways:

*Parallel*, that is, most all of the crystals may be parallel to one another, or very nearly so, when they may be *subparallel*. This fabric is found in some igneous rocks composed of lime-soda-feldspars and in others composed of potash-feldspars.

*Diverse*, omniversal, when the plates lie in all directions. This fabric is oftener developed when tabular crystals, feldspars, lie in all directions among other minerals, as in many ophitic rocks.

*Radial*, divergent, fanlike, or spherulitic in part, an arrangement oftenest seen in certain alkali-feldspar rocks, syenite-pegmatites.

*Tangential*, concentrically curved, or imbricated, like the leaves of an onion. An uncommon arrangement found in some aggregations of mica, as in the nodular granite of Craftsbury, Vt.

PRISMOID crystals may have arrangements analogous to those of tabular crystals, as follows:

*Parallel* or *subparallel*, when all, or most all, the prismoid crystals are parallel to one another. An arrangement found in certain alkali-feldspathic rocks that have cooled rapidly and are aphanitic, some trachytes and phonolites.

*Diverse*, omniversal, when the prismoid crystals lie in all positions.

*Radial*, divergent, spherulitic, axiolitic. An arrangement commonly found in certain lavas of highly siliceous rocks, spherulitic rhyolites, etc.

*Branching*, arborescent, also merging into radial, spherulitic, and occurring similarly.

*Tangential*, concentrically curved, or arranged parallel to the surface of a nuclear crystal.

IRREGULARLY shaped crystals forming equiform, equigranular rocks may be arranged with respect to one another in two ways. They may be in juxtaposition, or they may interpenetrate one another. These two relations may be described as follows:

CONSERTAL. — When irregularly shaped crystals in juxtaposition are closely fitted together, or conserted.

GRAPHIC. — When irregularly shaped crystals mutually penetrate one another, they often produce fabrics as in graphic granite, which have already been described.

***Arrangement in Inequigranular Rocks.*** — When rocks are inequigranular, hiatal, or seriate, the arrangement of the crystals may be described in the same terms as those just applied to equigranular rocks. But it sometimes happens that in porphy-

ritic rocks the arrangement of the phenocrysts is different from that of the crystals forming the groundmass, or it may be desirable to describe the arrangement of one independently of that of the other. Considering the arrangement of the phenocrysts in a porphyritic rock the following relationships may be recognized and described by appropriate terms:

*Scattered* phenocrysts, distributed more or less uniformly through the groundmass, produce a fabric that may be called SKEDOPHYRIC, the porphyry being called a SKEDOPHYRE. This is the commonest case.

*Grouped* phenocrysts may be arranged in several ways: (*a*) in *clusters* or irregular groups, producing a CUMULOPORPHYRIC fabric, the rock being a CUMULOPHYRE. A special case of this kind, with equant phenocrysts of pyroxene, has been called GLOMEROPHYRIC texture (glomeroporphyritic, Judd, 1886). (*b*) When phenocrysts are in *layers*, the fabric is PLANOPHYRIC and the rock a PLANOPHYRE. (*c*) Phenocrysts in *lines* or *streaks* produce a LINOPHYRIC fabric, the rock being a LINOPHYRE.

In like manner the inclosed crystals, or chadacrysts, in poikilitic fabric may be uniformly scattered, or grouped in various ways, within the oikocryst. When they are tabular or prismoid they may be parallel or subparallel to one another, or their arrangement may be omniversal or diverse.

***Branching and Radiating Crystals.*** — Special shapes and arrangements of crystals formed rapidly in viscous magmas, owing to their frequent occurrence, need more detailed description. They may be considered as branching and radiating crystals, and as parallel and subparallel aggregations, sometimes radiating.

There are several methods by which the branching of crystals may take place: (*a*) by the extension of a crystal in several different directions, producing what are sometimes called skeleton forms; (*b*) by curving and splitting and subsequent prolongation of prismatic crystals; (*c*) by successive growths of crystals attached to one another in more or less inclined positions.

(*a*) The result of extending a single crystal in several different directions depends upon the kind of crystals, and is oftenest

seen in the wonderfully varied and delicate hexagonal plates of snow, each one being a single tabular crystal. Tabular crystals almost never branch in this manner in igneous rocks. But such branching is known to take place with prismatic crystals, and to some extent with equant ones.

Slender microscopic prisms of potash-feldspar elongated in the direction of the *a* axis and twinned according to the Manebach law may extend for considerable lengths without branches, being more or less curved. At the extremity, however, they

FIG. 47.

may spread into somewhat tabular leaf-like shapes. Prisms of this kind may be branched by the prismatic extension of the same crystal at regular intervals on both sides of the twinned prism in the directions of the *c* axis, that is, at about 64 degrees to the direction of the *a* axis on each side, Fig. 47. In some instances the branches thin toward the extremity and curve. They are parallel to the same direction as that of the main prism, or stem, the *c* axis and *a* axis becoming parallel, Fig. 48. This kind of branching is found in certain spherulites in the obsidian of Obsidian Cliff.

Examples of the branching by extension of equant crystals

through addition of material in parallel molecular orientation are shown by some aggregated growths of magnetite, Fig. 49, and by certain microscopic crystals of leucite, Fig. 50, in leucitite in the Bearpaw Peak, Mont.

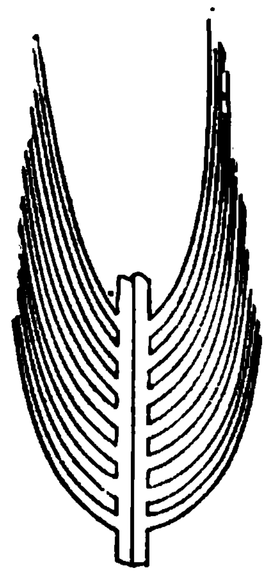


FIG. 48.

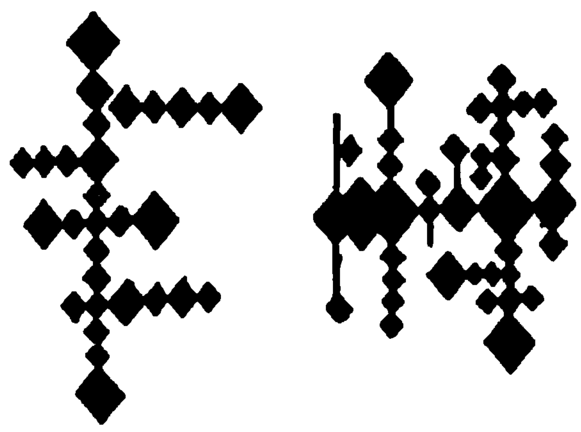


FIG. 49.

(b) The branching of prismatic crystals by curving and splitting, and further extension of the split prism, has been demonstrated by laboratory experiment by Lehmann and others.

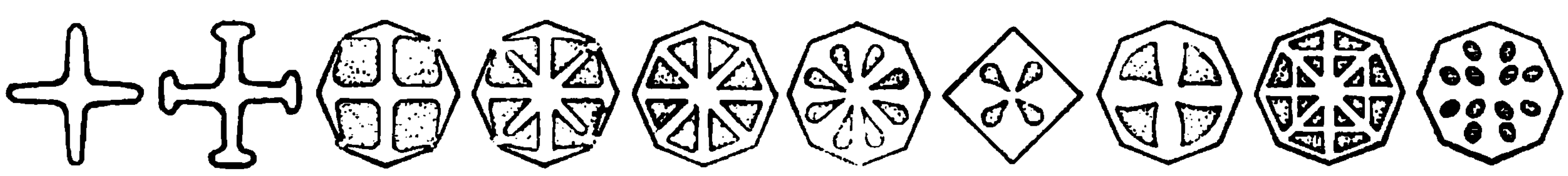


FIG. 50.

An extremely thin, fiber-like, prismatic crystal is apt to curve during its first growth in the longitudinal direction. Upon thickening, the orienting forces in the molecules set up stresses

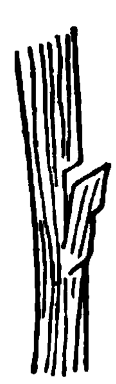


FIG. 51.

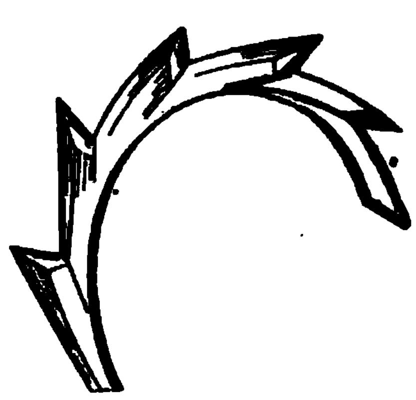


FIG. 52.

tending to straighten the curved crystal. This may lead to a fracture on the convex surface and the straightening out of a split portion of the curved prism, Fig. 51, which may grow on as a spur or branch, Fig. 52. In this way a feldspar prism

may branch or fork repeatedly, as in obsidian at Obsidian Cliff, Fig. 53. Both modes of branching may take place on the same crystals of feldspar. The result of repeated forking and branching leads to more or less radiating clusters of prismatic crystals, arborescent in arrangement, which often assume a spheroidal form and constitute certain kinds of spherulites.

FIG. 53

(c) Still another mode of producing branching arrangements of crystals is by the growth of one crystal at an inclination to another, the two being independently oriented individuals. This kind of branching may resemble very closely that produced by splitting in some cases. It takes place with feldspar prisms in the formation of certain spherulites, Fig. 54, and may occur in combination with the modes of branching first described. Spherulites of feldspar produced in the laboratory

are sometimes composed of extremely thin tabular crystals arranged in branching aggregations, which in thin section yield plumose and feather-like groups.[1] This mode of branching is

FIG. 54.

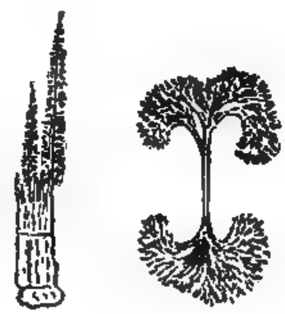


FIG. 55.

also developed in aggregations of pyroxene prisms in the pitchstone on Arran, Fig. 55, and in basaltic glasses, as on Hawaii, Fig. 56.

The most familiar example of such branching aggregations of crystals, prismatic and tabular, is the frost on a window pane.

FIG. 56.

***Radial, or Spherulitic, Crystallization.*** — This takes place for the most part in rapidly cooling viscous magmas, and is therefore specially common in rock glasses, that is, in rocks whose chief components are alkali-feldspar and quartz, and these minerals are the principal ones taking part in the result-

[1] The Isomorphism and Thermal Properties of the Feldspars. Carnegie Institution of Washington, 1905. Plates II, III, V, VII, VIII, XIII, XIV, XVI, XVII.

ing fabric. There are two modes of crystallization that yield radiating, or spherulitic, aggregations: one is the crystallization of compact, radiating, straight, prismoid crystals; the other, the growth of separated, radiating, branching, and often curved prismoid crystals. In certain cases the crystals may be flat prismoids, or thin plates. Since these are rapid growths all of the constituents of the liquid magma are generally inclosed within the space occupied by the spherulitic aggregation, so that the composition of the aggregation is usually complex. If the magma consisted of one compound the spherulitic growth would be composed of one kind of mineral. Radial, or spherulitic, fabrics are usually complex, containing all the minerals composing the liquid from which the crystallization takes place. Several definite kinds of these fabrics will be described in detail. The chief types have been taken from the spherulitic obsidian and lithoidal lava of Obsidian Cliff, Yellowstone National Park,[1] and from similar rocks at Rosita Hills and Silver Cliff, Colo.[2]

COMPACT, GRAPHICALLY INTERGROWN, SPHERULITES. — In this obsidian, which consists of 60 parts alkali-feldspar and 35 parts quartz, the two minerals in places begin to crystallize at the same time and together, producing microscopic groups of feldspars graphically intergrown with quartz, as shown by their shape, fabric, and optical behavior. A simple group of this kind magnified 235 diameters is shown in Fig. 57. The nature of its fabric is understood by comparing it with that of the graphic feldspar group, magnified 37 times, Fig. 22, p. 209, from a porphyry from Eureka, Nev.

When the number of feldspars combining in this way increases, the outline of each is lost and the effect in section between crossed nicols is shown in Fig. 58. With still further increase in the number of feldspar crystals radiating from a center the aggregates become more nearly fibrous in fabric and spheroidal in shape, Fig. 59. When still more regularly developed the nearly ideal spherulite is produced. A minute one

[1] Iddings, J. P. Am. Jour. Sci., 1887, vol. 33, p. 36, and Seventh Annual Report U. S. Geological Survey, 1888, pp. 249–295, and Bulletin Phil. Soc. Washington, vol. 11, 1892, pp. 445–463, also Mon. 32, Part 2, U. S. Geological Survey, 1899, pp. 410–422.

[2] Cross, W. Bulletin Phil. Soc. Washington, vol. 11, 1891, pp. 411–444, and Seventeenth Ann. Rept. U. S. Geological Survey, 1896, Pt. 2, pp. 263–403.

magnified 153 diameters is shown in Fig. 60. Such spherulites are compact and holocrystalline, and consist of radiating prisms of alkali feldspar with submicroscopic graphic intergrowths of quartz. This has been indicated by the resemblance between the minute feldspar clusters and certain graphically intergrown phenocrysts of the same minerals. It is shown also by the marginal crystallization of these spherulites in certain parts of

Fig. 57.

Fig. 58.

Fig. 59.

Fig. 60.

the rock of Obsidian Cliff, where it is seen that straight prismatic crystals of feldspar extend beyond the circumference of the central spherulite; are free from the minute inclusions producing the almost submicroscopic graphic fabric of the spherulite; are optically and, therefore, crystallographically continuous with the radiating crystals of the central spherulite; and are plainly prisms elongated in the direction of the *a* axis, Fig. 61.

It is further shown that the quartz that was excluded from these pure feldspar crystals subsequently crystallized outside of them in spaces between neighboring spherulites.

It appears that the conditions that permitted the spherulitic intergrowth of the feldspar and quartz changed, so that feldspar crystallized alone, free from quartz, which subsequently crystallized in relatively large crystals in spaces between inclosing spherulites. In some cases the free silica crystallized in these spaces as tridymite. The change of condition most likely to take place in a cooling magma, from which feldspar and quartz are separating, is a change in the relative amount of gas in the residual liquid magma, provided there is no means of escape. An increase in the gas content may change the saturation of the solution with respect to one of the components, which may cease to separate for a time. It is to be noted that in the graphically intergrown quartz and feldspar phenocryst from Eureka, Nev., Fig 22, p. 209, there is a margin of pure feldspar surrounding the quartz-filled portion.

FIG. 61.

The small amount of other components of the rock magma are scattered through the radial aggregation either as microlites that had formed prior to the spherulitic crystallization and became inclosed by it, or as microscopic crystals that may be arranged radially with the feldspar.

MICROSPHERULITIC fabric is one formed by small compact spherulites in juxtaposition, and therefore not strictly spherical in shape, but spheroidal to irregular in form. In each spherulite there is a point from which the crystals radiate, as shown by the optical behavior between crossed nicols, Fig. 62. Each is undoubtedly composed of feldspar and quartz intergrown in the manner described for larger spherulites.[1]

Similar radiating feldspars with graphically intergrown quartz crystallize in larger individuals in rocks of like composition with higher granularity. The spherulitic forms are less often developed, and frequently a phenocryst of feldspar or quartz serves as a nucleus for the radial aggregation. Moreover, there are fewer feldspar crystals in each aggregation. The graphic fabric is often clearly seen in thin section under the microscope.

[1] Iddings, J. P. Am. Jour. Sci., 1887, vol. 33, p. 36, and Seventh Ann. Rep. U. S. Geological Survey, 1888, p. 277.

Teall, J. J. H. British Petrography, London, 1888, p. 402.

Brögger, W. C. Zeitsch. für Kryst. u. Min., 1890, vol. 16, pp. 552–553.

An example of this micrographic fabric is shown in Fig. 21, p. 208, and has already been described.

SPHERULITES OF BRANCHING CRYSTALS. — In the same obsidian also occur radiating aggregates made up of prisms of feldspar, often not in contact with one another, which branch in ways

FIG. 62.

already described and illustrated in Figs. 47 and 48, p. 225. They assume a great variety of curved shapes, from spheroid to plumose.

A good example of such an arrangement is shown in Fig. 63, which represents a section across a large spherulite at a spot where a spheroidal surface, or zone, terminating closely parallel feldspar prismoids, minutely branched, is succeeded by a growth of larger, branched crystals. These in turn become more slender and more nearly parallel to one another. The spherulite occurs in rhyolitic lava at Rosita Hills, Colo. The spaces between the feldspar prisms may be filled with glass when the whole is a compact body, or they may be occupied by tridymite and gas cavities. The tridymite is then in minute spherical aggregates that formed after the feldspar crystallized.

Such spherulites are more or less porous. No quartz has been observed with the branching feldspars in the rock at Obsidian Cliff, except in the case of lithophysæ, where it appears to result from the reaction of gases upon crystals already formed.

FIG. 63. PART OF A SPHERULITE OF BRANCHING FELDSPAR CRYSTALS. (Cross, U. S. Geological Survey.)

The conditions controlling this mode of spherulitic crystallization are clearly those permitting the separation of feldspar without that of free silica which subsequently crystallized as tridymite. This action has been already referred to the presence of more vapor than was present when the compact, graphically intergrown spherulites form. It is probably dependent on viscosity, as affected by the gas content of a magma. When both kinds of spherulites are present in obsidian the compact kind is at the center, as the first formed, and is often surrounded by the porous, branching spherulites, which are usually much larger than the graphically intergrown, compact ones.

CONCENTRICALLY ZONED SPHERULITES. — Concentric zones or shells frequently develop within both kinds of spherulites. They consist in some cases of a comparatively narrow zone

marked by an accumulation of colored ingredients, iron-bearing microlites, or by a somewhat more compactly crystallized shell in the porous spherulites. Such variation in the crystallization of radiating crystals is due to changes of saturation in the liquid magma arising from the rapidity of crystallization of the prismoid minerals. For a sudden rush of crystallization may liberate sufficient heat to reduce the saturation of the surrounding liquid and even stop the separation of solid material until the diffusion of the heat permits saturation to rise again. A pulsation of crystallization in rapidly solidifying liquids can be observed in the laboratory under favorable circumstances.

FIG. 64.

HOLLOW SPHERULITES. — Some of the porous spherulites have openings in them of considerable size, evidently made by the shrinkage of the substance within the spherulite, for the openings take the form of gaping cracks, or cavities, which open toward the middle of the spherulite and do not extend beyond its outer surface, Fig. 64. The evident shrinkage must have followed a considerable condensation of the magma from a liquid state, when there was gas in solution, to that of crystallized feldspar and quartz, the gas having separated to occupy spaces between the crystals. The distinction between this mode of crystallization and that resulting in an ordinary, compact aggregation of conserted crystals of quartz and feldspar lies in the rapidity with which slender prisms of feldspar rush outward through a liquid magma and capture a spheroidal

body of it, establishing an outer boundary by the rapid formation of a shell of closely set minuter crystals. This structure appears to be strong enough in most cases to resist compression from the surrounding matrix when subsequent crystallization of the magma between the feldspar prisms results in the condensation already noted. Cases are known in which the spherulitic

FIG. 65. CRUSHED HOLLOW SPHERULITES. (Cross, U. S. Geological Survey.)

shells were not strong enough to resist the pressure of the surrounding liquid magma and collapsed, or fractured so as to permit the magma to enter the cavity, Fig. 65, from rhyolitic lava, Rosita Hills, Colo. But in these cases the viscosity of the magma was such that it did not completely fill the cavity within the spherulite. When ordinary crystallization takes place toward separated centers, the necessary condensation is accom-

panied by the shrinking of the liquid magma and the drawing nearer together of the centers of crystallization.

LITHOPHYSÆ. — When considerable shrinkage takes place in spherulites having concentric zones of different denseness of crystallization there result concentric shells with hollow spaces between, which have been called LITHOPHYSÆ,[1] or stone bubbles. These structures may be of great delicacy, composed as they are of minute crystals of feldspar, quartz, and tridymite, which sometimes adhere but slightly to one another, and seem in many cases

FIG. 66. LITHOPHYSA IN OBSIDIAN.

to have resulted from a recrystallization of the first formed crystals by the gases escaped from the crystallized magma. With them is associated fayalite, an orthosilicate of iron.

One form of lithophysa in compact obsidian is shown in Fig. 66, in which the delicacy of the concentric shells and the presence of an outer, more substantial shell are seen. In the laminated rock most of the lithophysæ are hemispherical or disk-shaped. The concentric shells partly curve over one another like the petals of a rose, Fig. 67. In some cases they are quite eccentric in shape. Other forms of lithophysæ in lithoidal rock are shown in Fig. 68. The original idea that they resulted from the expansion of gas bubbles within the magma is disproven by the fact that they have the radially prismoid structure of spherulites and certain other characters that may be represented by Figs. 69–75. Thus there are porous, radially prismoid spherulites partly hollow

[1] von Richthofen, F. Jahrb., k. k. geol. Reichsanst., vol. 11, 1860, p. 180.

Fig. 67. Lithophysa. (Merrill, National Museum.)

Fig. 68. Lithophysæ. (Merrill, National Museum.)

Fig. 69.

Fig. 70.

Fig. 71.

Fig. 72.

Fig. 73.

Fig. 74.

Fig. 75.

as in Fig. 69. In some instances such spherulites are traversed by parallel bands, in continuation of the planes of lamination in the groundmass of the rock, Fig. 70. Spherulites with concentric shells of growth are represented by hollow forms in which the denser zones appear as thin shells coated with crystals, Fig. 71. There are varieties of these crossed by layers in continuation of planes of lamination in the rock, Fig. 72. The hemispherulite with concentric zones, when developed in a narrow layer within laminated rock, spreads into the shape of a flattened disk, the bands farthest from the center being narrow segments of spherical shells, Fig. 73 and Figs. 67 and 68. Such forms are sometimes traversed by layers parallel to and in continuation of planes of lamination in the rock, Fig. 74. In some instances there are gas spaces in the rock connected with lithophysæ in such a manner as to appear to be the result of expanded gas, Fig. 75. But it can be demonstrated that the concentric shells are not the result of expanding gas, but of pulsating spherulitic crystallization accompanied by contraction of the original magma upon passing into the crystal phase.[1]

The ESSENTIAL CHARACTERISTIC OF SPHERULITIC CRYSTALLIZATION is the mode of aggregation of crystals which may be prismoid or tabular and may take on any outward form as an aggregation. The necessary mode of arrangement is radiating, it may be from a single point or from a number of points near one another. If radiation takes place from one or more points in a cluster, and proceeds at nearly the same rate in all directions, the resulting aggregation of radiating crystals is spheroidal in shape. If the rate of growth is more rapid in certain directions than in others, the shape of the aggregation is that of a curved body, plumose or more irregularly shaped. If the centers of radiation are in a line the resulting aggregate is cylindrical, straight, or curved, called an AXIOLITE. If the centers are in a plane the slightly radiating crystals form a layer like the pile of velvet, which in section resembles a slightly radiating fringe, Fig. 76, from Rosita Hills, Colo.

COMPOUND SPHERULITES sometimes grow to great size. In Colorado, at Silver Cliff, they reach a diameter of over ten feet

[1] Iddings, J. P. Seventh Ann. Rep., U. S. Geological Survey, 1888, pp. 266 and 285.

in some instances.[1] They appear to have been formed by the rapid growth of rays of plumose spherulitic aggregates outward from a central core and the final radial growth of a denser layer forming an outer spherical shell, Fig. 77. The whole of the inclosed rock, or magma, is not necessarily crystallized in radial arrangement. It may even be glassy in part. The character of the crystallization is the same as that of spherulites composed of

FIG. 76. SPHERULITIC CRYSTALLIZATION. (Cross, U. S. Geological Survey.)

branching feldspar prisms. They are in the nature of skeleton spherulites, and suggest such rapid growth that the plumose rays shut in as inclusions between them much magma that solidified in other ways.

In some instances the constituent crystals of spherulites are so delicate that they are with difficulty recognized by a microscope as being present. Their presence and arrangement are indicated by their optical behavior between crossed nicols, showing double refraction of radiating fibers.

[1] Cross, W. C. Bulletin Phil. Washington, vol. 11, 1892, pp. 411–443.

Fig. 77. Compound Spherulite. (Cross, U. S. Geological Survey.)

## HOMOGENEOUS AND HETEROGENEOUS TEXTURES

If a homogeneous texture be defined as that of a rock the cycle of whose crystallization has been alike throughout considerable volumes of the rock, then heterogeneous texture would be that texture in which in closely neighboring parts of a rock the cycle of crystallization was different. That is, within short distances of each other the fabric may be evenly granular, micrographic, spherulitic, or otherwise. Homogeneous texture may be produced by changes in the rate or character of crystallization, as in the case of porphyritic fabric, but in this case the same changes must have affected adjacent parts of the magma alike. Homogeneous texture may be highly complex and have an intri-

cate fabric. In a rock possessing a heterogeneous **texture**, differing from place to place in either crystallinity, granularity, or fabric, or in all three, it is evident that the magma must have been heterogeneous in composition or physical character, or both.

An excellent example of heterogeneous texture is the rock of Obsidian Cliff, Yellowstone National Park, which is for the most part microlitic glass with irregularly scattered spherulites of various sizes, with cylinders, streaks, and layers having microspherulitic fabric, and lithophysæ. Holocrystalline portions mingle with highly glassy portions, and porous textures with compact ones. A study of the rock has shown that the heterogeneity of the magma was probably confined to a variable content of water vapor or gas which affected the molecular mobility or the liquidity of the magma and controlled the mode of crystallization in various parts. Similar variations in texture occur in many highly siliceous lavas and are probably due to like causes. The more viscous the magma the greater the likelihood of there being an irregular distribution of gas which may have entered the magma from inclosing rocks. The less siliceous and more fluid magmas seldom exhibit such heterogeneity of texture.

Another case of heterogeneous texture is found in rocks often of intermediate composition, but also in others, in which in certain spots all the mineral components appear in relatively large crystals compared to those in surrounding portions of the rock. Apparently at these spots conditions existed favorable to the formation of large crystals. These were most likely greater molecular mobility of the magma, probably produced by a slightly greater content of gas, for a small amount that would initiate crystallization would remain in the liquid since it does not enter into the composition of most of the crystallizing solids.

Heterogeneous texture is characteristic of most pegmatite rocks, especially those composed of feldspar and quartz. In them coarsely graphic fabric and radial fabric commonly mingle with granular consertal fabric, which may be equigranular in some places and inequigranular in others, often varying greatly in granularity.

**Laminated, Banded, or Primary Gneissic Texture.**—Textures that may be described by any of these terms resemble one another in being more or less laminated, or in consisting of nearly parallel layers of different kinds of minerals or of tabular ones. But they differ in individual cases with regard to the essential character of the texture. Several types of cases may be recog-

nized as distinct in origin, but they may be blended in particular rocks whose texture may be due to several causes, each of which might alone produce lamination. In some cases the texture may be homogeneous and the rock homogeneous in composition; in others the texture may be heterogeneous and the rock essentially homogeneous in composition. In still other cases the rock may be heterogeneous in composition and the texture homogeneous or heterogeneous. Examples of these cases are as follows:

1. Rocks that are homogeneous in composition and texture may be characterized by parallel or subparallel, tabular or prismatic crystals of mica, feldspar, or hornblende, which produce a laminated texture, which may occur in a porphyritic rock or in a granular, nonporphyritic one. This is the texture of some gneissic rocks, which may be, in certain cases, unaltered igneous rocks in which some of the crystals were arranged in nearly parallel position by the movement or flow of the magma while crystallizing. Such a PRIMARY GNEISSIC texture is shown in the Twilight granite in the Needle Mountains Quadrangle, Colorado, Fig. 78, which was intruded between layers of amphibolite across which the granite has sent narrow offshoots of pegmatite.[1] The appearance is due to the arrangement of mica in parallel position and in streaks. In the phanerocrystalline granular rock (pulaskose) of Mount Johnson, Quebec[2] a laminated texture is due to the parallel arrangement of tabular or prismoid feldspars.

2. Rocks that are homogeneous in composition but are heterogeneous in texture and exhibit lamination are common among the highly siliceous lavas, and, strictly speaking, were not homogeneous in composition when liquid magmas, but contained different amounts of water vapor or gas in different parts of the magma. An excellent example is furnished by the lithoidal portion of the rock of Obsidian Cliff, which consists of thin layers alternately dense and microspherulitic, or porous and phanerocrystalline, almost equigranular. The lamination is due to the spreading of the lava during its flow, whereby slightly heterogeneous portions of any shape become more and more

[1] Cross, W. U. S. Geological Survey, Needle Mountains, Folio 131, Fig. 11.
[2] Adams, F. D. Jour. Geol., vol. 11, 1903, p. 260.

flattened, lenticular to discoid in shape, and eventually appear as thin parallel layers, differing in color and texture, which together form a continuous mass of rock.[1] While the process of flowing and spreading must be the same in all kinds of magmas, the more fluid and, therefore, the more homogeneous the

Fig. 78. Laminated Granite with Offshoots of Pegmatite.
(Howe, U. S. Geological Survey.)

magma the less sign of heterogeneity and of lamination in its fabric.

3. Rocks that are heterogeneous in composition, from causes that are discussed in the next chapter, after intrusion or flow, become laminated through the spreading out of the differently constituted portions into layers which may or may not crystallize with like textures. Such rocks appear banded because the layers are composed of different minerals, or the same minerals

[1] Iddings, J. P. Am. Jour. Sci., vol. 33, 1887, p. 36.

in different proportions. Examples of banded igneous rocks of this kind are found on the Isle of Skye, some being coarse-grained gabbros, others peridotites.[1] Similar banded gabbros occur in Canada, where other coarse-grained rocks exhibit the same texture in a very pronounced manner. In eastern Ontario,[2] syenite, nephelite-syenite, corundum-syenite, and a

FIG. 79. BANDED NEPHELITE-SYENITE. (Adams and Barlow.)

rock composed almost wholly of nephelite, monmouthose, are markedly laminated and gneissic. The primary lamination in the nephelite-syenite near York River Bridge, Dungannon township, is well shown in Fig. 79.

**Orbicular texture** in phanerocrystalline rocks is one produced by more or less spheroidal aggregations of megascopic crystals of various kinds, arranged in different ways in different occur-

[1] Geikie, A., and Teall, J. J. H., Quar. Jour. Geol. Soc. London, vol. 50, pp. 645–659.
Harker, A. Memoirs. Geol. Survey, United Kingdom, Glasgow, 1904, pp. 75, 90, and 119.

[2] Adams, F. D., and Barlow, A. E., Trans. Roy. Soc. Canada, 1908.

rences, but generally characterized by concentric shells composed chiefly of one or more of the component minerals. There appear to be several kinds of these spheroidal crystallizations which may have quite different origins,[1] one kind being in the nature of concentrically arranged segregations from a supposedly homogeneous magma; another, the recrystallization and rearrangement of the material of an inclosed rock melted and partly blended or dissolved in the inclosing magma. The discussion will, therefore, involve the subject of segregation of minerals in an igneous magma, on the one hand, and the problem of the melting and solution of inclosed rocks by molten magmas, on the other.

Of the first kind are certain spheroidal aggregations that consist at the center of large feldspar crystals with a somewhat radial arrangement, the outer portion of the spheroid consisting of more or less well-defined concentric layers rich in mica or hornblende. They seem to have a close analogy with the large feldspar phenocrysts, microcline, in rapakiwi granite in Finland and elsewhere, which often carry a spheroidal layer or layers of inclusions of mica and hornblende, with some quartz and an outer zone of oligoclase. In certain cases of spheroidal aggregations the spheroids are not larger than the largest phenocrysts in rapakiwi, consist of large multiple feldspars, somewhat radially arranged, that is, forming radiating segments of a spheroid. The outer portions of these spheroids are made up of crystals of mica, hornblende, and feldspar (Wirvik, Finland; and Fonni, Sardinia). This kind of aggregation appears to be one caused by a very uniform growth of feldspar in one crystal or radial aggregation of crystals, which excluded the ferromagnesian constituents until their accumulation supersaturated the magma in a spheroidal zone to such an extent that they separated in crystals about the feldspar nucleus. This process might repeat itself until several alternating zones of hornblende, biotite, and feldspar were formed.

In most cases the kernel of the spheroid is a granular aggregate usually of several kinds of minerals, feldspar, with quartz,

[1] Chrustschoff, K. von. Über holokrystalline makrovariolithische Gesteine. Mémoires Acad. Imp. Sci. St. Pétersbourg, VII Série, vol. 43, No. 3, 1894, pp. 1-245.

mica, or hornblende as the chief constituents. The fabric of the kernel may be without radial or concentric arrangement of any of the components; resembling the fabric of the surrounding rock, but differing from it in the proportions of the minerals, as is the case with some of the spheroids in granite near Fonni, Sardinia, Fig. 80. The kernel is surrounded by concentric spheroidal zones, usually rich in biotite and hornblende, with zones rich in feldspar, the character of the feldspar

Fig. 80. Spheroid from Granite, Sardinia. (Merrill, National Museum.)

differing in different rocks. Usually the composition of the spheroid is richer in lime, iron, and magnesia and poorer in silica than the surrounding rock, as though there had been a segregation of ferromagnesian and calcic minerals in the spheroid from the magma. Less frequently the spheroids are more siliceous and poorer in ferromagnesian minerals and feldspars than the surrounding rock. This is the case with the orbicular granite at Pine Lake, Ontario.[1] In either case it appears that it is the

[1] Adams, F. D. Bulletin Geol Soc. Am., vol. 9, 1898, pp. 163–172.

compound with the highest degree of saturation in the magma solution that segregates from it. Pine Lake rock has 78.83 $SiO_2$, the spheroid 81.43 $SiO_2$. The rock has about 42 per cent of quartz, the spheroid about 68 per cent quartz.

In some cases there is a noticeable radial arrangement of the minerals in the spheroid, as in those of the hornblende-granite of Rattlesnake Bar, Cal., in which amphibole, feldspar, and iron oxides are arranged more or less radially, without definite

FIG. 81. ORBICULAR TEXTURE IN DIORITE, CORSICA. (Merrill, National Museum.)

crystallographic orientation, however. The radial arrangement becomes more pronounced in the outer zones of the spheroid. This is the arrangement in spheroids in diorite from Corsica, Fig. 81, in which the central portion consists of granular diorite, the surrounding zones in part of radial crystals of bytownite feldspar, in part of feldspar with abundant hornblende and pyroxene. Similar spheroidal rocks occur at Altai, Siberia, Kunnerdorf, Silesia, and elsewhere.

In certain cases it appears as though the spheriods resulted

from the fusion and partial solution or blending, and subsequent crystallization, of mineral aggregations differing in composition from the surrounding magma. Such inclosed rock fragments may have been segregations from the magma of the rock in which they subsequently appeared as inclusions, or they may

FIG. 82. ORBICULAR TEXTURE, VIRVIK, FINLAND. (Merrill, National Museum.)

have been fragments of other kinds of rock picked up by the molten magma. Since they have been more or less completely melted and recrystallized their original character is often indeterminable. No attempt will be made in this place to discriminate between the two cases.

The spheroidal granite at Virvik, near Borga, Finland, is an example of the diversified character of these textures, several kinds of spheroids occurring in the same rock according to

Frosterus.[1] The more remarkable variety is shown in Fig. 82. These spheroids, 20 to 30 cm. in diameter, have very irregular shapes that suggest corrosion of more regularly shaped ellipsoids. The central part is nearly spherical, and in some instances consists of a granular aggregation of feldspar and biotite, in others of a single individual of oligoclase-albite. The outer zones consist of biotite with variable amounts of feldspar, and may be 40 to 50 in number. The spheroids appear to have been crowded together and distorted, fractured, or dissolved to different degrees as the illustration shows. This may have happened when the shells of mica had crystallized, but before the feldspar had solidified, and while the surrounding magma was still liquid.

An excellent example of partially dissolved fragments recrystallized as spheroids occurs in the granite of Kangasniemi, Finland.[2] According to Frosterus the kernel in most of the spheroids appears to be an inclusion of gneiss, sometimes changed by magmatic action to a granitic character. It consists chiefly of biotite, oligoclase, and quartz, with very little potash-feldspar. The concentric zones differ in composition in the following order: next to the kernel is a zone of coarse-grained andesine; with this are small amounts of oligoclase, potash-feldspar, quartz, and mica. The second zone is a fine-grained aggregation of biotite, andesine, orthoclase, and quartz, with small amounts of oligoclase. This is followed by a zone of microcline radially arranged and carrying quartz graphically intergrown. The outermost zone is a fine-grained aggregation of andesine, with some potash-feldspar, more quartz than in the inner portion of the spheroid, and some biotite. The surrounding rock consists of potash-feldspar, albite or oligoclase, quartz, and biotite.

It is to be remarked in this connection that the segregations by crystallization from an igneous magma often assume textures very similar to those of gneissic rocks, so that the presence of laminated fabric in the central portion of a spheroidal aggregation should not be used as a means of determining its original character.

[1] Frosterus, B. Tscher. Min. petr. Mitth., vol. 13, 1893, p. 177.

[2] Frosterus, B. Bulletin Com. Géol. Finland, No. 4, Helsinfors, 1896.

# CHAPTER VII

## DIFFERENTIATION OF ROCK MAGMAS

### EVIDENCES OF DIFFERENTIATION

WHEN a magma solution crystallizes into minerals of different kinds it is sometimes said to be differentiated into its component minerals, but this is not the ordinary application of the term DIFFERENTIATION to igneous rocks. By it is commonly meant the separation or splitting up of a homogeneous rock magma into chemically unlike portions. Evidences of such separation or differentiation may be classed under two categories:

1. One body of igneous rock may have different chemical compositions in different parts of it, which may either (*a*) be localized with respect to its boundary or form, or (*b*) may not be referable to the form of the rock body.

2. Rock bodies of various chemical compositions may be associated in such a regular manner with reference to their place of occurrence and their time of eruption, and may possess such chemical characteristics, that their previous existence as components of a homogeneous magma is clearly indicated. Each of these groups of evidences of differentiation will be described briefly and the possible conditions or causes giving rise to them will be discussed.

(1) **Igneous Rocks Differing in Chemical Composition in Different Parts.**—(*a*) VARIATION IN COMPOSITION LOCALIZED WITH REFERENCE TO THE FORM OR BOUNDARY OF THE PARTICULAR ROCK BODY. — Examples of this kind of variation are found in some dikes of igneous rocks in which the margins, or parts adjacent to the walls, have different chemical and mineral composition from the central portion. More commonly the sides of these dike rocks are richer in the ferromagnesian compounds and poorer in feldspars and quartz. In some cases, however, the reverse is true, the margins being the more siliceous or more feldspathic. It rarely happens that intruded

sheets or sills exhibit differences of composition in the central and surface portions. In one intrusive sheet among many associated sheets at Electric Peak, Yellowstone National Park, there is a notable difference in composition between the upper and lower parts of the sheet which was undoubtedly produced by differentiation. In some laccoliths, particularly those of Square Butte [1] and Shonkin Sag,[2] Highwood Mountains, Montana, there are marked differences of composition, the less siliceous portions, richer in ferromagnesian compounds, being located along the margin or walls of the dome-shaped laccoliths. In a large intruded mass of highly siliceous feldspathic rock at the southern end of the Gallatin Mountains, Yellowstone National Park,[3] the margin of the body is more siliceous than the central portion. In the dome-like intrusion of Mount Johnson, Quebec,[4] the outer portion is richer in feldspar, the ferromagnesian constituents becoming more abundant toward the central part of the mass.

(*b*) Differences in Composition not Locally Referable to the Form or Boundary of the Body of a Particular Igneous Rock are of two classes: ($b_1$) one where the rock varies in composition from place to place in such a manner that it appears to have been heterogeneous before it was intruded and before it crystallized; ($b_2$) another in which the igneous rock carries masses of rock composed of minerals resembling those in the surrounding rock, but in different proportions, as though certain components of the igneous magma had been segregated from the magma.

Examples of the first class are found in some large bodies of rocks composed chiefly of lime-soda-feldspar, pyroxene, and iron oxide, gabbro, which vary in proportions in alternate layers, producing a broadly banded texture resembling some gneisses. The lamination was produced by the flowing of a heterogeneous magma. Such rocks occur on the Isle of Skye,[5] both in large

[1] Weed, W. H., and Pirsson, L. V. Bulletin Geol. Soc. Am., vol. 6, 1895, pp. 389–422.

[2] Pirsson, L. V. U. S. Geological Survey, Bulletin 237, 1905, p. 43.

[3] Monograph 32, U. S. Geological Survey, 1899, pp. 64–69.

[4] Adams, F. D. Jour. Geol., vol. 11, 1903, p. 260.

[5] Geikie, A., and J. J. H. Teall. Quar. Jour. Geol. Soc. London, vol. 50, pp. 645–659, and Harker, A., Memoirs, Geol. Survey, United Kingdom, Glasgow, 1904, p. 90 and p. 119.

bodies and in narrow dikes; in Quebec, Canada,[1] and elsewhere. Similar heterogeneity obtains in certain igneous rocks composed of olivine, pyroxene, some feldspar, and other minerals in smaller amounts, peridotite. Layers or streaks richer in one or two of these minerals and poorer in the others alternate with one another in large intrusive bodies of this kind of rock in the Cuillin Mountains, Isle of Skye.[2] The heterogeneity may show itself in blotches or irregular patches, as well as in layers or bands. It is known in this form in some granitic rocks, and such streaks have generally been called SCHLIEREN. This kind of banding is highly developed in nephelite-syenite in eastern Ontario,[3] which in places is chiefly feldspar, in places almost wholly nephelite, with schlieren of biotite and a thoroughly gneissic texture, illustrated in Fig. 79, p. 245.

In some cases the variation in composition is gradual from one part of a rock body to another without repetition, as though the molten magma differed in composition gradually through large volumes, as at Yogo Peak[4] and at Haystack Mountain,[5] Mont.

Examples of the second class, or of segregated parts of igneous magmas, are of frequent occurrence, being found in almost all kinds of igneous rocks. The SEGREGATIONS resemble blocks or fragments of rock caught up by the magma during eruption. They generally differ from the inclosing rock by containing more ferromagnesian compounds, hornblende, pyroxene, olivine, biotite, etc., these minerals occurring in the main rock, often with the same chemical and optical characteristics, or with closely related ones. Less often the segregations are richer in quartz or feldspar than the surrounding rock. The texture of the segregated portion usually differs from that of the rock itself, being generally coarser grained, often very coarse-grained. The fabric of the segregations may vary greatly in neighboring fragments or blocks, being nearly equigranular in one, porphyritic in another, notably banded and laminated in others.[6] In

[1] Adams, F. D. Jour. Geol., vol. 11, 1903, pp. 239–282.
[2] Harker, A. *Loc. cit.*, p. 75.
[3] Adams, F. D., and Barlow, A. E. Trans. Roy. Soc. Canada, 1908.
[4] Weed, W. H., and Pirsson, L. V. Am. Jour. Sci., vol. 50, 1895, pp. 467 and 479.
[5] Emmons, W. H. Jour. Geol., vol. 16, 1908, pp. 193–229.
[6] Cross, W. Telluride Folio, No. 57, Geological Atlas, U. S. Geological Survey, 1899.

some occurrences the resemblance to schistose and gneissic textures of metamorphic rocks is striking and deceptive. The distinctive features of the segregations are the similarity of the component minerals to those of the inclosing rock and the absence of true metamorphic textures.

Segregations have also been called ENDOGENOUS INCLUSIONS. They appear to have been early crystallizations in a magma, and in some cases may have formed large bodies that were broken and carried up as fragments by the magma when it was erupted.

(2) **Igneous Rocks of Different Compositions Associated in Regular Manner with Reference to Place of Occurrence and Time of Eruption, and Possessing Certain Chemical Characteristics.** — Evidence as to the derivation of separate and diverse rock bodies by differentiation from some common parent magma rests upon a number of factors involving (*a*) their frequent association in widely remote regions; (*b*) certain chemical characteristics that distinguish the rocks of particular regions; and (*c*) the relation between the composition and order of eruption of different rock bodies.

(*a*) The association of different kinds of rocks in a similar manner in volcanic regions in various parts of the earth was noted by Scrope,[1] Darwin,[2] Dana,[3] and others, and was considered by them to indicate that all of the volcanic rocks of one region are derived by some process of separation from a common or parent magma. It commonly happens that in one volcanic region there are rocks rich in silica and alkalic feldspars, rhyolites, and those rich in ferromagnesian minerals and lime-soda-feldspars, basalts, and various rocks whose composition is intermediate between these extremes. This association recurs again and again, as in the volcanic districts of Great Britain, Austro-Hungary, Italy, Greece, and other parts of Europe; in the districts of Tertiary volcanic eruptions in many localities in the Rocky Mountains, the Great Basin, and the Cordilleran ranges within the United States; and in other parts of the world. A similar association of different kinds of coarsely

[1] Scrope, G. P. Volcanos, London, 1825.

[2] Darwin, Charles. Volcanic Islands, London, 1844.

[3] Dana, J. D. U. S. Exploring Expedition, Charles Wilkes, U. S. N., vol. 10, Geology, Philadelphia, 1849.

crystalline, intrusive rocks occurs almost universally. But the variations in composition both as to kind and extent are not the same in all cases, though very similar in many localities. Fuller statements and discussions of these variations will be found in subsequent parts of this book, Volume II.

(*b*) When the chemical composition of the different kinds of rocks associated together in different volcanic regions is investigated closely, it appears that there are chemical characteristics that relate the rocks of one region to one another and distinguish them from the rocks of some other region. Thus most of the volcanic rocks of central Italy are characterized by relatively high percentages of potassium; while most of the igneous rocks of the Christiania region, Norway, are relatively rich in sodium. The volcanic rocks of the Yellowstone Park have moderate amounts of potassium and sodium; those of the Crazy Mountains, Montana, are richer in sodium; while the igneous rocks in districts farther north, Bearpaw Mountains and Little Belt Mountains, are rich in potassium. Differences with respect to other constituents also exist. The analyses upon which the statements are based will be found in the second volume of this book. Such chemical differences must affect the character and proportions of the mineral components of the rocks of different districts.

***Petrographical Provinces.*** — A mineral and textural distinction between igneous rocks of different regions was noted by Vogelsang[1] in 1872 and expressed by the term *geognostische Bezirke.* Subsequently the same distinctions were recognized by Judd in studying the igneous rocks of Hungary and Bohemia, and regions so distinguished were called PETROGRAPHICAL PROVINCES, which he defined as those "within which the rocks erupted during any particular geological period present certain well-marked peculiarities in mineralogical composition and microscopical structure, serving at once to distinguish them from the rocks belonging to the same general group which were simultaneously erupted in other petrographical provinces."[2] In order to emphasize the magmatic relationship between rocks of a petrographical province, which fundamental relationship has

[1] Vogelsang, H. Zeitschr. deut. geol. Gesellschaft, vol. 24, 1872, p. 525.
[2] Judd, J. W. Quar. Jour. Geol. Society, London, 1886, vol. 42, p. 54.

been termed CONSANGUINITY,[1] Washington has employed the expression COMAGMATIC REGION [2] for such a province.

It follows from this that certain kinds of rocks, such as those composed chiefly of potash-feldspar, trachytes or syenites, or those characterized by quartz and lime-soda-feldspar, dacites or quartz-diorites, belong in particular local series or groups and are absent from others, and that two series from different petrographical provinces may grade through similar ranges of silica percentages but embrace different kinds of rocks, as, for example, the rocks of the Vesuvian district and those of the Yellowstone Park. Each local group of igneous rocks, however, is not necessarily distinguishable from every other group. There are many local series of rocks, often in one petrographical province, and also numerous provinces on the earth, the rocks of which are identical in minutest detail, as the rocks of the Great Basin, Idaho, Utah, and Nevada, and those of Hungary. Moreover, the boundaries of such provinces are not sharply drawn in nature. In some regions the transition from one province to another is abrupt, in others gradual. Recognizable chemical differences may exist between groups of rocks within less than a hundred miles of one another, as appears in the Wyoming-Montana region from the Gallatin Mountains [3] northward through the Crazy Mountains to the Little Belt Mountains.[4] On the other hand, broad general features may prevail over vast areas of the globe. Thus the great belt of the Cordillera stretching along the western sides of North and South America abounds in volcanic rocks belonging to a nearly uniform petrographical province. The rocks are not specially rich in alkalies, and contain normal amounts of lime, magnesia, and iron oxides. In North America this province extends eastward to the Rocky Mountains. As the front ranges of this mountain system are approached there is a gradual increase in alkalies, which show themselves in more frequent alkalic feldspars and in the appearance of rocks bearing nephelite, leucite, and the sodic pyroxenes and amphiboles.

[1] Iddings, J. P. Bulletin Phil. Soc. Washington, vol. 12, 1892, pp. 128–144.

[2] Washington, H. S. The Roman Comagmatic Region. Carnegie Institution of Washington, Publ. No. 57, 1906.

[3] Iddings, J. P. Jour. Geol., vol. 6, 1898, p. 106.

[4] Pirsson, L. V. Twentieth Ann. Rep. U. S. Geological Survey, 1900, Pt. 3, pp. 558–576.

Such rocks occur in Montana, Wyoming, South Dakota, Colorado, and Texas, also in Arkansas and in the more eastern states, and in Canada. In South America they are known to occur in Brazil.

These chemical qualities or peculiarities that characterize the igneous rocks of particular groups are like family traits of character, and indicate an intimate relationship and a common source for all the rocks of the group. They prove that the varieties of rocks occurring at a particular center of eruption have been derived from some magma common to the district. They are genetically related to some parent magma, and are in a sense *consanguineous*. And since the differences between the various rocks of one group are similar to those between various chemical and mineral facies of one rock-body, dike or laccolith, the processes by which differentiation took place in the two cases were undoubtedly similar.

(*c*) **Order of Eruption.** — There is a relation between the composition of volcanic rocks and the order in which they have been erupted. But this relation is not a simple one, the evidence of partial series of eruptions being often contradictory. The sequence first discovered and expressed by von Richthofen[1] when reduced to general terms is of very wide application, and is to the effect that in any region or period of volcanic activity the earliest eruptions are of rocks having an average or intermediate composition, and that subsequent eruptions are of magmas with more and more diverse compositions, the last eruptions producing the most diverse kinds. Some of the modes by which this order may be varied, or apparently reversed, will be understood after the following consideration of the probable course of differentiation.

**General Character of Differentiation.**—That the process which has produced the many kinds of igneous rocks in a region with all their transitions into one another is a process of differentiation of an originally homogeneous magma, and not the blending of two or more different magmas, as suggested by Bunsen,[2] is shown by the relation between the chemical results of the

[1] Richthofen, F. von. The Natural System of Volcanic Rocks, San Francisco, 1868.

[2] Bunsen, R. Pogg. Ann. d. Phys. u. Chem., Leipzig, 1851, vol. 83, No. 6, pp. 197–272.

process and the time of eruption within a period of volcanic activity. For a process dependent upon any set of physical conditions which continue for long periods of time must yield results that are to a considerable extent functions of time, that is, they must be accumulative. If the process were synthetic, or a compounding one, the mixture should be more complete the longer the process operated. On the other hand, if it is differentiating, the separation, or differences, should increase as time goes on. The igneous rocks in a large volcanic region have been erupted at widely remote times, which, though belonging to a connected period of volcanic activity, may represent ages. The physical conditions controlling differentiation must have existed throughout these vast lapses of time and have operated persistently or intermittently. The effect in either case must be accumulative.

The physical factors chiefly concerned must be changes of temperature, pressure, and the amount of dissolved gases. The amount and rate of change in these factors experienced by igneous magmas proceeding from depths within the earth toward the surface, owing to distance and rate of flow, to the size and shape of reservoirs or conduits, fissures or pipes, and to the temperature, permeability, and water content of the rocks traversed, must vary greatly in different cases. Consequently the course of events, and the exact character of the resulting rocks, and the precise order of their eruption, can never be identical in any two volcanic regions or at any two centers of eruption. There may, nevertheless, be certain general resemblances, as already pointed out.

Before discussing specific methods by which differentiation of homogeneous solutions may be accomplished, it may be well to consider some of the consequences arising from the application of the general principle of magmatic differentiation.

1. If differentiation is controlled by conditions or agencies external to the magma, which depend upon the environment of the magma and its change of position, then the results of differentiation should vary as the external conditions vary. It is not to be expected, then, that similar parent magmas will always yield the same results when differentiated, for they may have experienced quite different physical conditions.

2. Since the process of differentiation requires time, is progressive, and often continues for ages, it follows that eruptions from a reservoir in which differentiation is taking place will draw off magma whose constitution will depend on the phase of differentiation attained by the parent magma. The phase will depend on the time at which eruption takes place. Moreover, since differentiation necessitates the coëxistence of differently constituted derived magmas in different parts of the parent body or reservoir, the kind of magma drawn off will also depend upon the portion of the reservoir drawn from; and, since these derived magmas will undoubtedly possess different viscosities, the magma drawn off will also depend in certain cases on the size of the exit and on the rate of flow.

3. If, in any region of eruptive rocks, each body of rock were the immediate solidification of the magma drawn from one common reservoir, it would represent the phase of differentiation in the parent magma at the time when eruption took place. If, however, the erupted magma does not solidify directly, but remains in a molten condition within the fissure or conduit, a further differentiation of this magma may take place under conditions imposed by its new environment. In this manner differentiation may proceed simultaneously at quite different rates, and possibly with diverse results, in the parent magma and in the derived magma. Material, then, which through subsequent eruption may come to a place where it can solidify, may be derived from the parent magma or from the derived magma, and may represent different phases of differentiation. And since changes of temperature and of gas content are more marked nearer the earth's surface than at great depths, and should affect small bodies of magma more readily than large bodies, it follows that in a given length of time differentiation will proceed farther in magmas near the earth's surface than in those at greater depths. Owing to the great volume and extent of the deeper-seated magma reservoirs as compared with those located in fissures or volcanic conduits, the former may be termed *regional*, the latter *local;* and so it may happen that eruptions coming directly from the greater reservoirs may extend through wide regions and be called *regional*, and may exhibit less differentiation than those emanating from small reservoirs, which are more

restricted in their occurrence and may be called *local.* A regional series of volcanic eruptions is found in those great fissure eruptions of Idaho and Wyoming, including the plateaux of the Yellowstone Park, together with the ranges of volcanic breccia forming the Absaroka, Gallatin, and other mountain ranges. A local series of eruptions would include the breccias and lavas connected with one volcanic vent, such as that at Electric Peak or that in the Crandall Basin, in the same region.[1]

## PROCESSES OF DIFFERENTIATION

In discussing possible processes by which a differentiation of a homogeneous igneous magma may have taken place it is necessary to consider, first, the agencies or conditions which may produce changes in the physical and chemical status of different parts of a liquid rock magma, and, second, the character or results of such changes.

The *agencies* or *conditions* which may be appealed to as those most likely to affect to an appreciable degree the character of different parts of a body of liquid rock magma are (*a*) *changes of temperature;* (*b*) *changes of pressure;* (*c*) *loss or addition of gases.* There are other agencies which might take part in processes of magma differentiation, but which must play such insignificant rôles in most cases that their consideration may be omitted without seriously affecting the discussion. Such an agency is the passage of electricity through a molten magma, or a change in its magnetism. A change in the composition of a magma by the addition of material through the solution and diffusion of other rocks is not a differentiation of the magma, according to the definition already given, but is a process of solution and blending which will be considered independently.

*Changes in the temperature, pressure, or gas content of a portion of a magma solution* will affect to a greater or less degree one or more of the following physical or chemical characters of different portions of the magma:

(1) The *density* of the liquid, resulting in movements called *convection currents.*

[1] Iddings, J. P. Quar. Jour. Geol. Soc. London, vol. 52, 1896, pp. 606-617, and Monogr. 32, U. S. Geological Survey, 1899.

(2) The *viscosity* of the liquid, thereby modifying the internal friction of moving parts and the *diffusivity* of its molecules.

(3) The *osmotic pressure*, and consequently the *molecular concentration* in different portions of the magma.

(4) The *saturation* and eventually the *crystallization* in different parts.

(5) The *chemical equilibrium*, thereby affecting the combination of chemical elements and the resulting *mineral compounds*.

(6) The *character* of the *solidification*, or *crystallization*, and the resulting *texture* of the rock. This, however, is not properly a mode of differentiation. The effect of each of these changes upon a liquid magma and its possible bearing on the problem of the differentiation of a homogeneous rock magma will be discussed briefly.

(1) **Changes in Density.** — Change of temperature in liquid magma is accompanied by change of volume, an increase of one degree centigrade producing an expansion of 0.000050 in liquid basalt as determined by Barus.[1] A loss of heat must, therefore, be accompanied by a contraction of volume and a corresponding increase in density.

It is to be expected that change of pressure also produces change in volume, but it is known that the volume of a liquid is affected much less by changes of pressure than by those of temperature, and Barus[2] has determined the relation between these effects for liquid basalt, and has found that a change of pressure of one atmosphere is equivalent to a temperature change of 0.025° C. That is, a change of pressure by 40 atmospheres would be equivalent to a change of temperature of 1° C. It would require approximately 500[3] vertical feet of liquid magma of average composition to produce a pressure equivalent to 40 atmospheres, or offset a rise of temperature of 1° C.

It may be assumed that the density of rock magma decreases with increase of gas dissolved in it, and that it would increase as gas escaped from it by diffusion.

The behavior of a magma undergoing these several changes

[1] Barus, C. Am. Jour. Sci., vol. 42, 1891, pp. 498–499.

[2] Barus, C. Bulletin U. S. Geological Survey, No. 103, 1893, p. 53.

[3] More exactly, 542.4 feet (162.7 m.) of magma with a density of 2.5, or 452.0 feet (135.6 m.) of magma with a density of 3.0.

will depend upon its position within the earth, the shape of its body, and the environment which occasions the changes. It is necessary, therefore, to consider several extreme cases. The magma may be assumed to be homogeneous in composition and at rest, that is, without internal movement or currents.

(*a*) The magma may be of very great volume and of indefinite lateral and vertical extent. Such a mass of igneous magma may supply the volcanic rocks of a region like that of the Yellowstone National Park, where the different lavas that have reached the surface of the earth have been estimated to aggregate over 5000 cubic miles[1]; and it is not to be supposed that all of the magma leaving it reached the earth's surface or that the reservoir of magma was completely emptied. Whatever the depth at which such a body of magma may exist for some time, and whatever the pressure of the overlying rocks, it may be assumed that the reservoir is itself of such depth that the pressure of its own mass will be appreciable, so that the lower portion will be under greater pressure than the upper. The magma should, therefore, be the denser at the bottom by reason of the increase of pressure, and for slight depths of magma, such as 1000 or 2000 feet, the difference of pressure between the upper and lower parts may be taken as that due to the depth of the magma, 80 to 160 atmospheres approximately.

Assuming a gradual lowering of temperature from the center of the earth toward the surface, according to either the accretionary hypothesis of the formation of the earth or that of central solidification of a molten globe,[2] the upper portion of such a body of liquid magma should be at a lower temperature than the lower portion. How much lower will depend on the temperature gradient at the particular depth below the surface at which the magma is located. What this may be is not known, and upon this point hypotheses differ widely. According to Lord Kelvin's calculation on the assumption of a cooling liquid globe, the gradient for the first 200 miles from the surface would be roughly 1° C. for 250 feet and at greater depths a nearly constant temperature. According to the accretionary hypothesis of

[1] Iddings, J. P. Quar. Jour. Geol. Soc. London, vol. 52, 1896, pp. 611 and 614.

[2] Chamberlin, T. C., and Salisbury, R. D., Geology, New York, 1904, vol. 1, pp. 536 and 538.

Chamberlin the gradient varies with the depths, being quite low for the first 400 miles, only about 1.6° C. per mile for the first 200 miles, about 4 degrees per mile for the next 200 miles, and 5.4 degrees per mile for the next 200 miles. This latter rate is about 1 degree for 1000 feet of depth; the first mentioned only about 0.3 degree for 1000 feet. The effect of differences of temperature upon a body of magma at very great depth must be slight and of the same order as that produced by differences in the weight of the magma itself. If the increase in density in the lower portion of the magma due to pressure is greater than that in the upper portion due to slightly lower temperature there can be no convection currents induced by differences of temperature and pressure.

Should gas be dissolved in the magma homogeneously, and not able to escape, the effect of differences of pressure and temperature in the upper and lower portions of the magma may be such as to counterbalance one another; the discussion properly falling under case 3, since it is a question of osmotic pressure and molecular concentration. There may be a gradual diffusion of gas from one portion to another without the production of convection currents in the magma. Under the conditions postulated a deep-seated magma may remain at rest for an indefinite period.

(*b*) The magma may be situated as an intruded body between walls having a lower temperature than the liquid magma. It may be considered as having come to rest so far as its flow as an erupted body is concerned, and as having considerable depth. The upper portion of such a body of intruded magma must have a lower temperature than that of the deeper portion, because it has been encountering cooler walls and has been heating them as it flowed, so that deeper parts of the same body of magma flowed between warmer walls than the advance portion. It may happen, however, that there is the same difference in temperature between the upper portion and its adjoining walls as that between the lower portion and its walls, so that the rate of cooling in both portions of the magma may be the same at a particular period of time.

The effect of cooling at the walls of the magma body will be to increase the density of the liquid magma near the walls in a

gradual manner, so that the nearer the surface the denser the liquid, until a depth within the body is reached which may have a constant temperature in certain cases. There will result a tendency for a differential flow due to differences of density in the liquid, the greater velocity occurring nearest the surface of the body of magma, other things being uniform. Of course the surface of the magma immediately in contact with the wall rock will not flow but will adhere to it. The hotter and lighter magma in the center of the body will rise and in this way a circulation of magma may be inaugurated. Irregularities in the contour of the wall rock will give rise to irregularities of current, resembling eddies, with spaces in which there may be very slight circulation. The maximum velocity of movement will depend on the rate of cooling and the effect of the change of temperature on the density of the magma, and this will undoubtedly vary with the composition of the magma. Moreover, the marginal portion, or layer, of the body of magma will, in the case of broad bodies, move relatively much faster than the central portion, which being of large bulk will rise comparatively slowly in order to supply the descending marginal flow. In general it may be expected that cooler wall rocks will be encountered by an intruded magma the nearer the earth's surface. But it may happen that previously erupted magmas heated the wall rocks, even to a very considerable height, so that a newly intruded magma finds itself surrounded by heated rocks quite near the earth's surface, as in the conduit of a volcano.

Differences of pressure at different depths within the body of magma, so far as they increase the density in the lower portion, tend to hinder a vertical circulation, but with notable differences in temperature the effect of pressure becomes negligible.

The effect of a change in the gas content on the density of the magma will be in one of two directions according as gas escapes from the magma into the surrounding rocks or enters the magma from the wall rocks. In case there is a loss of gas it may take place at the walls and be followed by diffusion from within the magma. The operation is similar to that of the diffusion of heat, and the effect will depend on the rate at

which escape takes place and diffusion follows. It is possible that the escape is sufficient to affect the density of the magma to a greater extent near the walls than at the center of the magma body. It will then act in the same direction as loss of heat, and promote the downward movement of the outer portion of the magma so far as a change in density alone is concerned. If gas is added to the magma, it will decrease the density of the magma, being most effective nearest the walls of the body, and thus tend to offset the effect of loss of temperature, so far as density is concerned.

The foregoing discussion applies to bodies of magma of considerable vertical extent intruded in cooler rocks. The case of magma lying nearly horizontally in an intruded sheet is somewhat different. The cooling takes place from the upper and lower surface at about the same rate in most cases. The denser layer at the bottom should remain there; the denser layer at the top of the sheet having its character changed gradually may have but a slight tendency to move downward. If it should set up convection currents they would only affect the central and upper portion of the sheet. In a sheet of moderate depth the effect of differences of pressure must be inconsiderable. Changes of gas content act with or against loss of heat as the case may be.

2. **Changes in viscosity** result from changes in temperature and especially in gas content, and to a much less extent from changes of pressure. Viscosity may be highly developed in rock magmas, particularly those rich in alkalic feldspar and quartz molecules. The range of variability in viscosity consequent upon change of temperature and gas content appears to be much greater than changes in density for corresponding temperature changes. Viscosity increases with loss of heat and of gas and with increase of pressure. The more viscous a liquid, the greater the internal friction, the slower the flow for given differences of density in a rock magma. The greater the viscosity the slower the molecular diffusion of gas.

The influence of increased viscosity on the convection currents in rock magma just discussed is such that it must cause a slowing of the cooler portions about the margin, or walls, of a magma body. Whether this slowing offsets the acceleration

due to increase of gravity will depend on the relative values of each, concerning which we have no data at present. Loss of gas with loss of heat would intensify this retardation. Accession of gas from the wall rock by lowering the viscosity sufficiently may accelerate the movement due to increase of density, or it may just offset the increase of viscosity due to loss of heat.

In magmas of different composition, convection currents, so far as they are influenced by viscosity, should be least active in the more siliceous and alkali-feldspathic magmas, and most active in those low in silica and alkalic feldspathic molecules.

3. **Molecular concentration** varying with osmotic pressure is affected by changes of temperature in different portions of a solution. The principles regarding this relationship have been stated in Chap. III, p. 103. In general it may be said that when two parts of a homogeneous solution are at different temperatures there will follow a concentration of certain molecules toward the colder part in order to maintain equilibrium of osmotic pressure throughout the solution. It may be expected, then, that when a body of homogeneous magma is at uniform temperature throughout there will be no change of molecular concentration due to the temperature. If the magma is inclosed by cooler rocks, and there results a difference of temperature in different parts, certain compounds will diffuse toward the cooler parts. The rate of diffusion will be greater the greater the difference of temperature between neighboring parts, that is, the greater the temperature gradient between the surface and interior of the magma body. The rate of diffusion will be greater the more fluid the magma; that is, the higher its temperature, the greater the gas content, and the more its composition is favorable to liquidity for any given temperature. The presence of $H_2O$ and other gases at high temperature, under sufficient pressure to hold them in solution, must greatly increase molecular mobility in rock magmas. On this subject, however, we have no data at present.

As the time required for the diffusion of notable amounts of material under ordinary conditions in a motionless solution is very great,[1] and as it is promoted by reducing the distance through which diffusion must take place, the differential flow of

[1] Becker, G. F. Am. Jour. Sci., vol. 3, 1897, pp. 21–40.

magma along the walls of its reservoir must furnish a constant supply of differently heated layers of liquid in contact with one another and thereby greatly shorten the time required for producing notable diffusion. A gradual diffusion of the molecules "in solution" toward the cooler portions of the magma must take place. Whether the results of this molecular concentration are appreciable or not depends on the factors just mentioned — temperature gradient, liquidity, gas content, and chemical composition of the magma. In such vertical currents the effect of pressure in any horizontal plane disappears. It might modify the results in the upper and lower portions of very deep reservoirs.

In the general statement of the law of molecular concentration toward cooler parts of a solution the substances that become more concentrated are those said to be "in solution." But in solutions all compounds are properly in solution in one another, all are "in solution." The custom of calling one part of a solution the solvent and the others the substances in solution, or solutes, has arisen from the constant use of aqueous solutions in the laboratory. By analogy with ordinary aqueous solutions of salts those compounds that separate early from a solution are thought of as the things in solution, and the compound remaining liquid longest is called the solvent. Such terms have no proper application to rock magmas and are often misleading. The substance, or substances, which will concentrate toward the cooler parts of a rock magma are those which would saturate the solution earliest, upon change of condition. They are those that would crystallize first, or earliest. They must, therefore, be different in different magmas according to the chemical composition. They may be ferromagnesian and calcic in some magmas; alkalic, aluminous, or free silica in others. But since the liquidity of magma is greater the richer it is in the first-named compounds, the extent to which molecular concentration may take place will be greater in the less siliceous rocks, other things being equal. As to the molecular character of the compounds which may diffuse and concentrate in any portion of a magma solution, it has been pointed out that the compounds in a magma must be more or less complex molecules corresponding to definite mineral compounds, which, however,

may be ionized to a greater or less extent according to temperature, molecular concentration, and other conditions. They are mostly silicates, with a few oxides, $SiO_2$, $Fe_2O_3$, $Al_2O_3$, and other non-silicates in some cases. The components do not exist as uncombined oxides,[1] with limited exceptions. They do in part exist as ions, but it is known that ions do not diffuse independently of one another in solution, except under the influence of an electric current. Consequently the compounds which diffuse to produce the proper degree of molecular concentration must correspond to definite mineral compounds. To some extent they diffuse as ionized compounds and are capable of chemical reaction and readjustment according to the attendant conditions as discussed in Chapter III. Thus it is possible for a compound like that of muscovite ($H_2KAl_3(SiO_4)_6$) to be concentrated in one part of a magma, and subsequently to break up under changed conditions, yielding, $H_2O$, $KAlSi_3O_8$ and $Al_2O_3$; or water, orthoclase, and corundum. It is possible that in this way magmas rich in corundum have originated.

The diffusion here described must produce a differentiation of a homogeneous magma into portions of different compositions. It is a differentiation that antedates crystallization, which may, or may not, take place while the magma is in the reservoir where differentiation occurred. It may be called MOLECULAR DIFFERENTIATION. It is occasioned chiefly by unequal distribution of temperature; is promoted by convection currents; and is, undoubtedly, greatly affected by the presence of gas at high temperature dissolved in the magma. It is more likely to take place in the more liquid magmas, and, therefore, in those of particular compositions, and in those intruded at higher temperatures. It is more likely to take place in bodies of magma with considerable vertical extent, with steep, or sloping, walls; and rarely in horizontal sheets, or sills. Where cooling is so rapid as to solidify a magma in comparatively short time,

[1] The statement by the author* in 1892 regarding the probable chemical composition of the components of molten magmas which emphasized the lack of absolute fixedness of the compounds, was in error in asserting that they do not correspond to definite mineral compounds, and that they behave as simple oxide molecules. The assertion has unfortunately gained a wider circulation than it deserved.

* Iddings, J. P. The Origin of Igneous Rocks, Bulletin Phil., Washington, 1892, vol. 12, p. 158.

there will have been no opportunity for differentiation of this kind to have taken place to an appreciable extent. It may not be expected in bodies of rapidly cooled rocks, intrusive and extrusive, especially in the more siliceous varieties.

4. The **saturation,** and eventually the *crystallization,* of certain compounds in the magma is affected by changes of temperature, pressure and gas content, and it is possible for a differentiation of a homogeneous magma to be brought about by the crystallization and movement of the crystals, or of the uncrystallized magma. To what extent this has resulted in differentiating large bodies of magma may appear from the discussion that follows. The problem may be considered in the abstract, and then for specific cases.

It is well known that ordinarily when crystals form in an aqueous solution they settle to the lower part of the solution; they are precipitated. By analogy with the behavior of many aqueous solutions it has been assumed that when crystals form in a rock magma they should settle or float, according to their relative density when compared with that of the liquid magma. This analogy was made use of by Charles Darwin [1] in 1844; by Lyell [2] in 1855; by Scrope [3] in 1872; by King [4] in 1878; and more recently, by others,[5] who have sought by this means to explain the differentiation of rock magmas. For it has been argued, that by the crystallization of ferromagnesian silicates and iron oxides, which are heavier than liquid rock magmas, and by their settling to lower parts of the magma, the latter would become richer in these constituents. If the temperature is higher in the lower parts of the magma the precipitated crystals may be melted, and the lower part of the magma remain liquid. If crystals form that are lighter than the magma they should rise and the upper part of the magma become richer in these compounds. Whether such a process takes place to an appreciable extent in rock magmas depends upon the difference in density between the crystal and the liquid magma; the size

[1] Darwin, C. Volcanic Islands, London, 1844, pp. 117–124.
[2] Lyell, C. A Manual of Elementary Geology, New York, 1855, p. 522.
[3] Scrope, G. P. Volcanoes, Second Ed., 1872.
[4] King, C. U. S. Geol. Exploration of the Fortieth Parallel, Washington, 1878, vol. 1, p. 705, *et seq.*
[5] Daly, R. A. Jour. Geol., vol. 16, 1908, pp. 401–420.

and shape of the crystal, the viscosity of the magma, and the length of time taken to bring about the complete crystallization of the magma.

The difference in density between the ferromagnesian minerals and the average magma is sufficient to cause them to fall through the action of gravity if the liquid were very fluid. But rock magmas are more or less viscous near the point of saturation, the more siliceous ones exceedingly so. And the tabular and prismoid shapes of many crystals greatly increase the surface relative to the mass. Moreover, most crystals are very small, so that the resistance offered by a viscous liquid is relatively great. The necessary data for the proper statement of the relationships are wanting. In the absence of definite knowledge that would permit a reliable statement of the probability of such separation taking place to a notable extent, the evidence from the rocks themselves may be applied to the solution of the problem.

Bodies of igneous rock which are exposed for hundreds of feet seldom, if ever, exhibit recognizable differences in composition in upper and lower portions. Great vertical exposures of rock of intermediate composition appear in most cases to be homogeneous rock, as, for example, the mass of El Capitan in the Yosemite Valley, California. In most intrusive sheets there is no appreciable difference in composition between upper and lower portions, and the same is true of most sheets of lava, though the rock contains crystals of magnetite scattered through it with a density nearly twice that of the magma. In one intrusive sheet at Electric Peak, Yellowstone National Park,[1] there is a notable difference between upper and lower portions, which is shown by the presence of phenocrysts of pyroxene in the lower portion which are not in the upper, and by the chemical analyses of both parts. In the massive sheet of igneous rock forming the Palisades, New Jersey, which is composed largely of lime-soda-feldspar and augite, there is a layer near the bottom rich in olivine, which appears to have settled after crystallization.[2]

[1] Iddings, J. P. Monograph 32, U. S. Geological Survey, 1899, p. 82.
[2] Lewis, J. V. Ann. Rep. Geol. Survey, New Jersey, 1907, p. 125 and pp. 129–133.

Instances have been mentioned by Darwin[1] and by King,[2] of volcanic lavas in which the lower portions contain phenocrysts of feldspar which do not appear in the upper part, and these have been taken as evidences of the settling of crystals in rock magmas. It is to be pointed out, however, that in the absence of definite information as to differences in the chemical composition of the upper and lower portions of these lava sheets, the presence of crystals in the lower and not in the upper portion of a lava stream may be the result of differences in conditions which affected the viscosity and eventually the crystallinity of the two parts, for the upper portion of a lava stream cools much faster than the lower.

The absence of evidence of any appreciable amount of settling of crystals in most solidified igneous magmas indicates that in these cases the viscosity of the liquid was such that no considerable precipitation could take place, or that there were other hindrances. Some idea of what these may have been may be gotten from a consideration of the probable act of separation of solids from mixed solutions, especially liquid rock magmas. In general it may be said that in most cases of solidification of rock magmas supersaturation sets in because of the very gradual rate of cooling. This may attain a high degree in most cases. Crystals then begin at comparatively close points, and grow rather rapidly. There is probably not much of a time interval between the starting of one kind of mineral and that of another. The evidence in the case of many rocks is that nearly all kinds of minerals crystallize at the same time, which is in accord with the theory of the separation of solids from mixed solutions of physically similar substances capable of dissolving one another at somewhat similar temperatures. The eutectic mixture should contain some of all the components of the original solution. The simultaneous crystallization of many crystals of different kinds of minerals, some heavier and others, in some cases, lighter than the liquid magma, often in tabular and prismoid shapes, would interfere with the differential movements of the various crystals. They undoubtedly adhere to one another, and soon the magma is so filled with growing crystals

[1] Darwin, C. Volcanic Islands, London, 1844, pp. 117–124.

[2] King, C. U. S. Geological Exploration, Fortieth Parallel, 1878, vol. 1, p. 716.

that they become virtually stationary, or their relative motions become negligible. This appears to be the common experience of most intruded, or extruded, bodies of rock magma, so far as their exposed portions indicate.

It is possible that crystallization may set in when there is only a slight amount of supersaturation and continue so gradually that the separated solids may move appreciable distances before being interfered with. But the slower the rate of change of temperature, the more likely a high degree of supersaturation will be reached before crystallization begins. If such a separation by precipitation should take place, it is most likely to occur in the least viscous magmas, that is, the least siliceous and alkali-feldspathic, or those richest in lime, magnesia, and iron-oxide. It is possible that some bodies of iron oxides associated with igneous rocks may have been formed by the precipitation of these oxides from the accompanying rock magmas.

It has also been suggested that segregations in igneous rocks may have arisen through the settling of early crystals into deeper parts of a body of magma, where they may have formed a solid mass, which might have been broken into fragments during subsequent eruptions of magma.

While partial crystallization and differential movement may take place under favorable conditions of liquidity and slow crystallization, and may result in the differentiation of some rock magmas, it is probably not the cause of lateral differentiation of dikes, laccoliths, and similar bodies of magma. It is doubtful, also, whether it should be applied to the differentiation of magmas which can be shown to be completely liquid at the time of their eruption and intrusion among other rocks, for it assumes a crystallization and melting of all crystals and becomes purely hypothetical. A case which might happen, but of which there can be no positive proofs.[1]

**Contemporaneous Veins.** — It is possible after a considerable portion of the magma has separated as crystals, that the liquid in which these crystals are suspended may be made to flow into openings formed by the fissuring of completely solidi-

[1] See also objections to the hypothesis of differentiation by partial crystallization by Pirsson in his monograph on the igneous rocks of the Highwood Mountains, Mont. Bulletin 237, U. S. Geological Survey, Washington, 1905, p. 186.

fied parts of the body of magma, chiefly the outer portions. This would result in a differential flow of the liquid and suspended crystals of such a nature that the liquid would drain off, as it were, and at some distance become nearly free from the crystals previously formed in it. This mode of differentiation is found in some veins of igneous rock that traverse the outer portion of certain bodies of igneous rock, and have varying compositions, which in the extremities of the veins correspond to the compounds that crystallize last in the main body of rock, and gradually change by increasing amounts of the earlier crystallizing compounds, until the vein merges, or blends, into the main mass of rock. Thus a dark gray, phanerocrystalline, granular rock composed of lime-soda-feldspar, hornblende, pyroxene and biotite, with small amounts of potash-feldspar and quartz, may be traversed near the margin of the body by narrow veins of lighter-colored rock, having similar texture and fewer ferromagnesian constituents. Such veins, toward their outer ends, become poorer in these minerals, and richer in potash-feldspar and quartz; eventually becoming white, and highly quartzose. In the other direction they become more and more like the main body of rock, until they merge into it without demarcation; that is, they are the same rock.

Such veins are called CONTEMPORANEOUS VEINS, because their intrusion is contemporaneous with the crystallization of the main body of rock with which they are associated; the rock into which they were intruded being still hot, as is shown by the granularity of the vein rock. This, however, may be due in large part to the gases that were probably concentrated in the magma penetrating the vein. This conception of a possible differentiation of a partially crystallized magma was expressed by Darwin[1] in 1844, but was not applied to contemporaneous veins.

**Pegmatite Veins.** — Some contemporaneous veins are called PEGMATITES, a name first used by Haüy for rocks made up of very coarse crystals, often several meters long. But the distinctive feature of pegmatites is not the large size of the component minerals, for pegmatites are sometimes fine-grained. They are characterized by the texture as a whole, and the composition in

[1] Darwin, C. Volcanic Islands, London, 1844, pp. 117–124.

certain cases, together with their association with larger rock bodies; that is, their occurrence as contemporaneous veins. There is no specific texture peculiar to pegmatites, but the occurrence in most cases of heterogeneous texture, with abrupt changes from one kind to another throughout the body of the pegmatite mass, which may range in size from a dike-like body, hundreds of meters wide, to veins only a few millimeters thick. The commonest textures are graphic, sometimes called pegmatitic for this reason, and granular consertal; besides miarolitic, in which the cavities are frequently relatively large. In certain instances there is an arrangement of some of the crystals with reference to the sides of the veins, as though crystallization started along the walls; and commonly there is a localization of exceptional minerals near the miarolitic cavities, or upon the walls of such cavities.

The principal minerals composing pegmatites are usually those that crystallize among the last in the main body of rock from which the pegmatites appear to have been derived, chiefly alkalic feldspars and quartz. With these are frequently associated exceptional minerals containing the rare earths, and elements found only in traces in ordinary igneous rocks, especially boron, fluorine, phosphorus, chlorine, sulphur, etc.

The concentration of these elements in magmas rich in alkalic aluminous silicates, and uncombined silica; the frequent occurrence of cavities in the rocks, and the generally large size of the crystals, together with the relationship between the pegmatite and the associated bodies of igneous rocks, all tend to show that pegmatites are derived from other rock magmas by processes of differentiation somewhat similar to those suggested for the production of simple contemporaneous veins, with greater prominence of the rôle of gases. Their production may be as follows:

The crystallization of part of the components of a molten magma into silicates containing no water, or almost none, increases the molecular concentration of the gaseous components of the solution in the remainder of the magma. An increase of these components lowers the freezing point of the compounds still in solution, and increases the fluidity of the liquid. There may result in this way a highly fluid solution, relatively rich in water vapor, or gas, and in other components having similar

action upon silicate solutions; that is, those known to promote molecular mobility, and called crystallizers, or mineralizers, as already explained. In this more gaseous portion may be concentrated those elements, or compounds, especially soluble in such a solution, which according to Arrhenius [1] would be those yielding univalent ions, such as compounds of chlorine and fluorine with the alkali metals, and with the alkaline earths and the rare earths; also of zinc, tin, copper, iron, and lead. Other compounds readily soluble in water are those yielding ions of boric acid, phosphoric acid, carbonic acid, and hydrogen sulphide. Thus the more gaseous solution may become richer in alkalies than the original magma, and there may be a concentration of lithium, often present in notable amounts in pegmatites. In this way there may be a concentration of compounds containing the rare earths; and those with fluorine, boron, and chlorine; others with columbium, tantalum, phosphorus and sulphur.

The segregation of such residual magma may result in there being portions of a body of igneous rock which are characterized by the constituents just mentioned, or in its eruption and intrusion into cracks and fissures, and the production of veins or dikes of pegmatite. The presence of considerable gas, and the consequent fluidity of the magma, permit the growth of large crystals, and the correspondingly greater shrinkage of the more gaseous magma accounts for the greater size of the miarolitic cavities. And it is to be noted, that the crystals immediately adjoining the cavities are often larger than those at a distance, corresponding to the greater hydration of the last portion of the magma to crystallize within the body of the pegmatite; in which portions the rarest compounds, or minerals, are generally located, as though parts of the last concentration.

The preponderance of silicates and quartz in these rocks, and the dominance of graphic intergrowths which indicates the simultaneous crystallization of compounds, commonly in eutectic mixture, together with the relatively small size of the miarolitic cavities as compared with the volume of the whole pegmatite

[1] Arrhenius, S. Zur Physik des Vulkanismus, Geol. Fören. Förh., Stockholm, 1900, vol. 22, p. 417. See also a paper by Grubenmann, U., Vierteljahrsschrift d. Naturf. Ges. Zürich. Jahrg. 49, 1904, pp. 376–391. For a discussion of pegmatites see Brögger, W. C., Zeitschr. Kryst., vol. 16, 1890, p. 101.

rock, show that the amount of gases concentrated in such magmas was not many times that of the gases originally distributed throughout the magma from which the pegmatite was differentiated; possibly not more than ten times as much. In fact, there are all gradations from rocks which may be called pegmatites to those which do not differ in any way from ordinary igneous rocks, some of which may be called contemporaneous veins.

Those minerals that appear to depend largely upon the action of gases in magmas for their presence in igneous rocks have been called PNEUMATOLYTIC; as have also the processes, involving gases, that have produced them. But gases are present in all igneous magmas, and the extent to which they may have influenced the crystallization of any mineral is not always demonstrable, consequently a distinction between what may be classed as pneumatolytic, and what may not, cannot always be made.

5. The **chemical equilibrium** between the elements composing a rock magma must be altered to a greater or less extent by changes in temperature, pressure, and gas content. And this should result in differences in the minerals that separate from different parts of a magma. Should these remain where they crystallized there would result differences in the mineral composition of various parts of the rock body, but not in the chemical composition. Such mineral differences would not constitute a differentiation of the magma in the sense here employed. If differential movement, convection currents, took place, there might result a differentiation of the magma, which would differ in the chemical character of the results according to the kinds of minerals separated from the magma. It might happen, then, that differentiation of chemically similar magmas by partial crystallization would result differently according to the conditions of temperature, pressure, and gas content attending the crystallization of each magma. At present this is purely a hypothetical mode of modifying the chemical composition of igneous magmas.

## FACIES OF IGNEOUS ROCKS

A FACIES of an igneous rock is any variation of the rock mass which distinguishes a part of it from the main body of the rock, either chemically, mineralogically, or texturally.

**Chemical facies** may be brought about by differentiation of a homogeneous magma by any of the processes just discussed, and may have taken place *in situ*, or before the magma was erupted and intruded into the place where it solidified. Chemical facies may also result from the melting and solution of other kinds of rock by a liquid magma. A discussion of this operation will be found on p. 280. In this case also solution may have taken place *in situ*, or before the eruption of the magma to its place of solidification.

**Mineral facies** may result in some instances from the presence of chemical facies; the chemically different parts of a magma crystallizing into different kinds, or into different proportions of the same kinds of minerals. Mineral facies may also result from the existence of different temperatures, pressures, or amounts of gas in various parts of a homogeneous magma. This is the kind of variation brought about by changes in chemical equilibrium already discussed. A further discussion of the results of changes in chemical equilibrium follows along the lines marked out in Chapter IV. The chief factor which may change the chemical equilibrium among the elements in a rock magma is the variation in chemical activity of hydrogen, or hydroxyl, at different temperatures, and with different degrees of saturation of this element, or compound, or radical; affected by differences of pressure. The rôle of hydrogen has been suggested and discussed in Chapter IV. Its chief function would seem to be to hold some of the silicic acid in combination at high temperature under sufficient pressure, and prevent its combination with other base-forming elements. It thus enters certain silicate molecules, as those of the micas and pyrogenetic amphiboles. It may prevent silicic acid from combining to a fuller extent with the base-forming elements, and allow silica to separate in an uncombined state after the breaking up of the hydrogen silicate, or orthosilicic acid, in the presence of a lower silicate of these elements. That is, quartz may separate from magmas

together with olivine, in place of hypersthene; quartz and muscovite may form in place of orthoclase or leucite; quartz and biotite may form in place of orthoclase and hypersthene; and so on.

It happens, then, that a magma may crystallize under one set of conditions into certain minerals, such as soda-orthoclase, quartz, with some pyroxene and magnetite, and the same magma under other conditions may crystallize into orthoclase (microcline), albite-oligoclase, quartz, with a little muscovite and biotite. Or, in another case, a magma may crystallize into potash-bearing lime-soda-feldspar, pyroxenes (augite and hypersthene) with some magnetite and a little quartz, and the same magma under other conditions may crystallize into lime-soda-feldspar, orthoclase, hornblende, biotite, and more quartz than in the first instance. In each of these cases the first example represents the mineral composition of a surface lava, and the second example that of the coarsely crystalline intrusive rock having like chemical composition.

Less pronounced differences in mineral composition may occur in different parts of one body of chemically homogeneous intrusive rock. Thus it may happen that a rock, in one portion, may consist chiefly of feldspars, pyroxene and some quartz, and in another portion there may be hornblende and biotite besides some pyroxene. Moreover, the hornblende and biotite generally crystallize later than the pyroxene and some of the feldspar, so that it may be concluded that the conditions favorable to the formation of hornblende and biotite obtained after the pyroxene had begun to separate from the magma. Referring the formation of hornblende and biotite to the influence of hydrogen, it would appear as though the separation of the earlier compounds from the magma solution by reducing the volume of the liquid increased the relative amount of hydrogen, or hydrogen compounds, in the remaining magma, and thereby brought about conditions favorable for the formation of the hydrogen-bearing compounds, hornblende and biotite. Such a relationship between these minerals is found in the igneous rock at Electric Peak, Yellowstone National Park,[1] and in various other places.

[1] Iddings, J. P. Twelfth Ann. Rept., Part I, U. S. Geological Survey, 1892, p. 606, and Monograph 32, Part 2, U. S. Geological Survey, 1899, p. 101.

Mineral facies of this kind may be looked upon as the result of changes in chemical equilibrium that have occurred *in situ*, the position of the magma not having changed since the crystals were formed under any particular set of conditions. There are other cases in which it is evident that after certain minerals had formed under a given condition of chemical equilibrium, the magma containing them moved by eruption to where conditions and the chemical equilibrium were different, with the result that the first separated compounds became unstable in the magma out of which they had crystallized, and consequently underwent a molecular readjustment, either to new solid compounds, or to liquid solution in the magma. Examples of such changes are found in the black borders of hornblendes in many lavas low in silica; and in the paramorphs of hornblende, consisting of pyroxene, magnetite, and often feldspar, already described in Chapter IV. Other examples are furnished by the quartzes in some basalts, which show by the zones of glass and augite crystals around them that they were being dissolved by the magma when the rock solidified.

**Textural Facies.** — Portions of a rock body having different texture from the main mass of rock are called TEXTURAL FACIES. From the discussion of texture in Chapter VI it is readily understood how differences of temperature, pressure, and gas content in various parts of a body of magma will produce differences in the crystallinity, granularity and fabric in different parts of the rock body. Thus it may happen that an intruded magma may cool so rapidly at the margins that crystallization may have begun here before the magma came to rest, so that phenocrysts of certain minerals formed during the eruption; that these were followed by a rapid crystallization of the magma at the margin of the mass, forming a porphyritic facies with aphanitic groundmass. The central portion of the magma cooling slower may have crystallized to a phanerocrystalline, equigranular rock, like a granite. Offshoots, or apophyses, from the large intrusive body, may have been chilled to aphanitic rock. Such a body of intrusive rock occurs at Eureka, Nev.,[1] and may be found in many other regions of igneous rocks.

In some surface lavas the upper portion of the sheet may be

[1] Hague, A. Monograph 20, U. S. Geological Survey, 1892, p. 223.

highly glassy, and when pumiceous it may be almost free from microscopic crystals; the lower portion of the lava may be holocrystalline and aphanitic. Such is the case with many highly siliceous lavas. The margins of some basalt dikes are glassy, the central portion highly crystalline, or holocrystalline. When the fabric of many rocks is considered closely, textural facies will be found to be still more common.

### SOLUTION OF ROCK BY LIQUID MAGMA

In order that a rock which has become inclosed in liquid rock magma, or has become adjacent to a body of intruded magma, should be dissolved by the liquid magma, it is necessary that it should be heated to near its melting point, or to near the eutectic point of the mixture of the two rock masses, unless there were a chemical reaction between the liquid and solid, which might produce a new compound liquid at some temperature lower than those mentioned. In the case of most rocks and molten magmas the chemical reaction possible between the base-forming elements and the silicic acid that may be available is an extremely sluggish one, unless it be accompanied by high temperature. When hot magma comes in contact with rock at much lower temperature it is necessary that heat be diffused from the liquid to the rock to raise its temperature to near the melting point, and the act of liquefaction of a solid absorbs a considerable amount of heat. This reduces the temperature of the liquid magma, and whether liquefaction of the solid takes place, or not, depends on the excess of heat in the molten magma above its freezing point, or that of the new mixture which should form from the magma and dissolved rock. If the temperature of the magma at the time of its intrusion is so high that it can part with enough to melt the adjacent rock and remain a liquid itself, the rock may be melted and dissolved by the intruded magma, provided it is liquid enough to permit diffusion of the adjacent liquid molecules. The solution of rock by an intruded magma is then a possibility under proper conditions. But to what extent is it probable that it takes place under the conditions ordinarily attending such intrusions? The answer to this question must be found in the composition and contact phenomena of igneous

rocks themselves. The evidences required are of two kinds: those relating to changes in the rocks invaded by intrusive magma; and those in the body of the intruded magma.

Evidences of melting of rock adjoining intruded igneous magma are sometimes found in very thin films or layers of glass a few millimeters thick along the contact of certain volcanic lavas with various kinds of rocks, but not between bodies of phanerocrystalline intrusive rocks and adjacent rocks. This is explained by the fact that a chilling, or rapid cooling, took place in the first instance, permitting the melted layer to chill to glass; whereas the cooling in the second instance, being slow enough to permit the intruded magma to crystallize completely and megascopically, also permitted the melted layer along the contact with the adjacent rock to crystallize in like manner. In the case of intrusions of some magmas that have crystallized coarsely there are evidences of profound changes of crystallization in the adjoining rock, which may, or may not, be accompanied by changes in chemical composition. Such changes belong to the problem of contact metamorphism. Whether such changes were accompanied by melting, or not, may not be determinable. But changes in the composition of adjoining rocks may be brought about by infusion of vaporous solutions from the molten magma, a mode of impregnation not strictly a solution of the rock by the molten magma. Evidences of this kind of action are oftenest met with where carbonate rocks are invaded by igneous magmas, the carbonates being decomposed and more or less replaced by silicates, when there is silica available for the reaction. Should this not be the case, the carbonate may remain a carbonate, even when it has been inclosed, and possibly dissolved, in the igneous magma. This is well shown in the contact phenomena along the margin of large bodies of nephelite-syenite, and of sodalite-bearing pegmatites of this rock, in Dunganon township, Eastern Ontario.[1] Where they have traversed limestone, calcite is found disseminated through the rock in coarsely crystallized individuals in juxtaposition with nephelite, sodalite and albite; and only a small amount of calcium silicate has been produced. While in the same region where quartzose rocks, granites, are in contact with limestone, calcium silicates, scapolite, epidote,

[1] Adams, F. D., and Barlow, A. E. Trans. Roy. Soc. Canada, 1908.

pyroxene and amphibole have been formed, the results being more pronounced where there has been pneumatolytic action. Evidences of chemical reactions are not commonly found where the invaded rock is already composed of silicates, unless a thinly fissile structure permits actual intrusion of liquid magma along planes of cleavage.

Evidences of absorption by the igneous magma of material from adjoining rocks are very slight, even in cases where these rocks have been profoundly affected by the intruded magma. There appears in most cases to have been almost no solution and diffusion of material from the adjacent rocks; the chemical composition of the igneous rock is not different where it is in contact with quartzite, limestone, or silicate rocks of various kinds. In many cases of fine-grained intrusive, quartzose igneous rocks there is no evidence of appreciable reaction between the igneous rock and the invaded rock, even where this is a carbonate. It commonly happens that blocks, or fragments, of rocks are inclosed in molten magma without exhibiting evidences of solutional reaction between the magma and inclosed blocks. The contact surface between them is frequently distinctly recognizable, there being no evidence of blending. Few statements as to signs of solution and diffusion of rock by igneous magmas have been substantiated by chemical evidence of a change in the intrusive igneous magma, due to such a reaction.

It appears from a study of intruded igneous rocks that they were not sufficiently heated to melt, or dissolve, invaded rocks to any appreciable, or at most to any considerable, extent. In many cases the temperature was near that of saturation for some of the components, and often near the point of solidification of the whole magma, as shown by the minuteness of the crystals formed and by the absence of metamorphism in the adjoining rocks. And in some cases of profound metamorphism of the surrounding rocks it appears to have been escaping gases that effected the change, the igneous rock exhibiting no signs of reaction.

On the other hand, there are instances in which very considerable blending of two igneous rocks, or their magmas, appears to have taken place. This is not a common phenomenon,

however, and seems to occur most conspicuously on the Isle of Skye according to Harker.[1] In this region of igneous rocks and volcanic eruptions there are intimately associated intrusions of magmas rich in ferromagnesian compounds and low in silica, gabbros, and others rich in alkalic feldspars and silica, granites. These have been intruded in contact with one another in large bodies that crystallized coarse-grained, and in numerous nearly horizontal sheets and vertical dikes, where the magmas cooled to finer-grained rocks. Along the contact between these bodies of different rocks there has been a blending which varies in degree in different instances, and is of such a nature that the more siliceous magma appears to have been intruded through fissures already occupied by the less siliceous magma before this had cooled appreciably, and in some cases apparently before it had completely crystallized. This, then, is a blending by mutual solution and partial diffusion of still heated rock by molten magma, or of two magmas. This process requires the eruption of a second magma into fissures occupied by a previous magma only just crystallized. The blending appears to follow the fracturing of the first rock into small fragments among which the intruded magma may permeate. It is not to be expected that molecular diffusion will effect much of a blending unless convection currents set in to promote the mixture.

**Hybrid Rocks.** — According to Harker there are bodies of rock, marscoite, which appear to represent a thorough blending of the two magmas prior to their intrusion into the places where they have solidified. Such rocks have been called HYBRID ROCKS.

Eruptions of magmas at short intervals through the same fissures, or conduits, are not infrequent occurrences at volcanic centers, and in most instances magmas that succeed one another before much cooling has set in, usually have very similar chemical compositions. In such cases the contact of earlier and later magmas results in welding, or blendings that are scarcely noticeable, or appear as compositional facies of one body of rock. This is the character of the somewhat variable stocks of igneous rock at Electric Peak and on Hurricane Ridge in Crandall Basin in the Yellowstone Park region.[2] It is not probable,

[1] Harker, A. Memoirs of the Geol. Survey of the United Kingdom, The Tertiary Igneous Rocks of Skye, Glasgow, 1904, p. 170, *et seq.*

[2] Monograph 32, U. S. Geological Survey, 1898, p. 97 and p. 246.

however, that in these cases there has been much transfusion of material from one magma to another after intrusion. The possibility of blending two liquid magmas, or of changing the composition of a molten magma by the solution of rocks through which it was intruded, have been made the bases for certain hypotheses concerning the origin of various kinds of igneous rocks.

### HYPOTHESES AS TO DIFFERENTIATION OF IGNEOUS ROCKS

The following very brief sketch presents some of the hypotheses that have been suggested in explanation of the diversity and genetic relationship of all igneous rocks at one center of eruptive activity. In 1825 Scrope suggested that in some crystalline rock, like a granite, a process of "intumescence" took place, due to interstitial water being highly heated and dissolving part of the quartz, accompanied by the volatilization of the mica, the gaseous portion being forced out by pressure, and the concentration and crystallization of this elsewhere.[1] It is interesting to note in this connection the idea of selective fusion and solution of material at great depth within the earth as the first source of rock magma, suggested by Chamberlin and Salisbury.[2] In 1844 Darwin[3] suggested that the partial crystallization of a molten magma followed by the precipitation of the crystals, or the draining away of the liquid, would produce the differences among genetically related igneous rocks.

The precipitation of crystals in molten magmas has been adopted as a whole, or in part, as a possible explanation of magmatic differentiation by Lyell,[4] Jukes,[5] King,[6] Brögger,[7] Teall,[8] Schweig,[9] Daly,[10] and others.

[1] Scrope, G. P. Volcanos, London, 1825, pp. 21-26.
[2] Chamberlin, T. C., and Salisbury, R. D. Geology, New York, 1904, p. 601.
[3] Darwin, C. Volcanic Islands, London, 1844, pp. 117-124.
[4] Lyell, C. A Manual of Elementary Geology, New York, 1855, p. 522.
[5] Jukes, J. B. The Student's Manual of Geology, Edinburgh, 1857, p. 81.
[6] King, C. U. S. Geological Expl. Fortieth Parallel, Washington, 1878, vol. 1, p. 705, *et seq.*
[7] Brögger, W. C. Zeitschr. fur Kryst. u. Min., vol. 16, 1890.
[8] Dakyns, J. R., and Teall, J. J. H. Quar. Jour. Geol. Soc., London, 1892, vol. 48, pp. 104-120.
[9] Schweig, M. Neues Jahrb., für Min., etc., B. B. 17, 1903, pp. 516-564.
[10] Daly, R. A. Festschrift zum Siebzigsten Geburtstage von Harry Rosenbusch, etc., Stuttgart, 1906, 203-233. And Jour. Geol., vol. 16, 1908, pp. 401-420.

In 1849 J. D. Dana[1] suggested that in the conduit, or liquid body, of a volcano the magma consisted of compounds of different viscosities, such as feldspar and pyroxene; the vaporizable ingredients tending to inflate the mass as it approached the surface, lowering the density of the more liquid portion, urging it upward more freely and thus causing a separation. He also considered the magma as made up of compounds not necessarily having fixed molecules, but as being capable of entering various compounds according to conditions of temperature, pressure and rate of cooling. This capability of forming different minerals under different conditions was recognized also by Roth[2] in 1861, and is now generally accepted as an established fact.

In 1851 Bunsen[3] advocated an entirely different hypothesis to account for chemical differences among igneous rocks of one region. It was the blending of two magmas of extreme composition to form rocks of intermediate composition. It required the existence of reservoirs of magma of the extreme types, but none of intermediate character. The two magmas were called trachytic (feldspathic) and basaltic (pyroxenic).

In 1853 von Waltershausen[4] explained the differences in the composition of igneous rocks as due to the depth below the surface of the earth from which they were erupted, on the assumption that the material of the interior is arranged in zones of greater density from the surface downward. This was supposed to accord with the generalization, commonly accepted at that time, that the most ancient igneous rocks were highly siliceous, or granites, and the most recent ones highly ferromagnesian, or basalts.

In 1857 Durocher[5] suggested the existence of superimposed magmas within the earth, somewhat analogous to those assumed by von Waltershausen. They were chiefly two, like those of Bunsen, but there was an inconsiderable zone between them, which furnished "hybrid" rocks. He also suggested the possi-

[1] Dana, J. D. U. S. Expl. Exped. Charles Wilkes, U. S. N., Philadelphia, 1849, vol. 10, p. 372, *et seq.*

[2] Roth, J. Gesteinsanalysen in tabellarischer Übersicht, etc., Berlin, 1861, p. xxi.

[3] Bunsen, R. Pogg. Ann. d. Phys. u. Chem., vol. 83, 1851, pp. 197–272.

[4] von Waltershausen, S. Über die vulk. Gesteine in Sicilien und Island, etc., Göttingen, 1853.

[5] Durocher, J. Ann. des Mines, 1857, vol. 11, pp. 217–259.

bility of a differentiation of magma erupted from this reservoir after it had entered fissures, the process being one of "liquation" similar to that known to take place in alloys. This is a process of partial crystallization, which was first suggested by Darwin. Durocher recognized the result of such a process operating differently in different branches of a system of fissures, producing local variation among igneous rocks.

In 1858 von Cotta [1] advanced the hypothesis that the upper portion of the earth, the crust, consisted of highly siliceous rocks, while the molten magma beneath was highly ferromagnesian, and that as this was erupted through the solid rocks it melted and dissolved various amounts in different instances. This is differentiation by assimilation.

In 1878 King [2] elaborated the theory of local differentiation by combining a number of previous ideas. The material of the earth was assumed to be arranged in layers of increasing density and differing composition downward, but remained solid until brought into a liquid condition by change of temperature and pressure. Then followed partial crystallization and precipitation, and then eruption.

In 1888 Teall [3] suggested that the concentration of certain molecular compounds in the colder part of a solution may cause the differentiation of rock magmas. This process, first known as Soret's principle, has been advocated by Vogt [4] and Iddings.[5]

In 1889 Rosenbusch [6] adopts the theory of differentiation of rock magmas, and suggests the existence of certain chemical compounds, "kerns," as the units of differentiation and the bases of distinction for certain classes of rocks. He does not advocate any particular process by which differentiation may be accomplished.

In 1890 Brögger [7] suggests that molecular diffusion toward

[1] von Cotta, B. Geologische Fragen, Freiberg, 1858, p. 78.
[2] King, C. U. S. Geol. Expl. Fortieth Parallel, Washington, 1878, vol. 1, p. 705.
[3] Teall, J. J. H. British Petrography, London, 1888, p. 403.
[4] Vogt, J. H. L. Geol. Fören. i. Stockholm Förhand., 1891, vol. 13, p. 476.
[5] Iddings, J. P. Bulletin Phil. Soc. Washington, 1892, vol. 12, pp. 193–197.
[6] Rosenbusch, H. Tscher. min. petr. Mitth., 1889, vol. 11, pp. 144–178.
[7] Brögger, W. C. Zeitschr. fur Kryst. u. Min., 1890, vol. 16.

the cooler portion of a magma (Soret's principle), accompanied by partial crystallization of the "more basic" minerals, may have brought about differentiation. This hypothesis has been advocated with some modifications by Dakyns and Teall,[1] Becker,[2] Washington,[3] Pirsson,[4] and Schweig.[5]

For a fuller discussion of theories of differentiation the student is referred to a paper on "The Origin of Igneous Rocks," by Iddings,[6] and one on "Differentiation der Magmen," by Schweig just cited.

### MAGMA ERUPTION AND DIFFERENTIATION

Without attempting to follow to its ultimate analysis the problem of vulcanism, but starting with the existence of highly heated rock material under great pressure at great depths beneath the surface of the earth, it is desirable to consider its possible condition before eruption, as well as its experience in moving upward and out upon the earth's surface.

The high temperature of volcanic lavas when they reach the atmosphere; the fact that they were losing heat continually from the time of their first movement upward; the evidence that they were completely liquid at some stage in their eruption, together with the observed gradient of heat increase downward from the surface of the earth, all combine to show that rock magmas come from some region where the temperature is considerably above the melting point of igneous rocks. The behavior of the earth as a rigid globe, and the known effect of pressure in counteracting that of heat, together with its estimated high gradient of increase downward within the earth, force the conclusion that at sufficient depth magma, though hot enough to be liquid, behaves as a solid. Such conditions of heat and pressure cannot vary abruptly from place to place, but must be nearly the same for large volumes of material; and differences of temperature and pressure must obtain very

[1] Dakyns, J. R., and Teall, J. J. H. Quar. Jour. Geol. Soc., London, 1892, vol. 48, pp. 104–120.
[2] Becker, G. F. Am. Jour. Sci., vol. 4, 1897, p. 257.
[3] Washington, H. S. Bulletin Geol. Soc. America, vol. 11, 1900, p. 408.
[4] Pirsson, L. V. Bulletin U. S. Geological Survey, No. 237, 1905, p. 187.
[5] Schweig, M. Neues Jahrb. für Min., etc., B. B. 17, 1903, p. 516.
[6] Iddings, J. P. Bulletin Phil. Soc., Washington, 1892, vol. 12, pp. 89–213.

gradually, chiefly in a vertical direction. Magma in such a position must be in a virtually static condition until it experiences change of pressure or stress; whatever its composition, it must remain unchanged.

A change of stress may come about by movement in the overlying portion of the earth. Orogenic movement, readjustment of the upper, rigid, rock masses from whatever cause, when profound must affect the stresses in still deeper parts. The known crustal movements behave as bendings of the upper rock mass which in places at the earth's surface appear to result in tensile stresses, in places in compressional stresses. Beneath each of these the effective stresses must be of the opposite kind; under the tensile, compressive stresses; and under the upper compressive ones, tensile stresses. Tensile stresses should occur at some distance below ocean beds, and more especially along the borders of oceans and continents. Compressive stresses should occur, in general, beneath continental masses.

Tensile stress, as at the bottom of a synclinal arch, operating in a rigid mass must communicate itself downward as far as the mass behaves rigidly. Where the hot mass is potentially fluid, that is, is kept solid by pressure, change of stress must be followed by change of position of the mass. A tendency to pull apart or stretch in the potentially fluid mass must be followed by a yielding of the mass. At a point sufficiently cool for the mass to act as a solid a tendency to fracture and to open a fissure would be followed by a movement of the slightly more heated mass beneath to occupy the space between the fractured solid. These differences of temperature and of rigidity are to be understood in a mathematical sense as differential; there being a gradation of physical conditions between adjacent parts of the mass. There will be no open space, or fissure, in the ordinary sense. But it must be understood that at whatever depth the mass may be considered solid, there it may fracture, part, and become the walls of a layer or body of intruded liquid, provided the liquid have nearly the same density as the solid mass. The statement made by Hoskins,[1]

[1] Hoskins, L. M. Sixteenth Ann. Rept. U. S. Geological Survey, 1896, Pt. 1, pp. 845–872.

that open cracks, or fissures, cannot exist at greater depths than about 10,000 meters, was made on the assumption that the filling is water; the difference in weight of the rock and the hydrostatic pressure of the corresponding column of water being compared with the crushing strength of the solid rock. When the liquid is heavier than water the same method of calculation allows fissures filled with such liquid to exist at greater depths; and if the weight of the column of liquid equals that of the wall rock, the two will remain in equilibrium at any depth. Consequently, at any depth in the earth's mass where a tendency to part may exist, hotter and potentially more fluid material beneath may move up and permit the parting of the slightly more rigid mass to take place. This would appear to be the initial step in the eruption of rock magma.[1]

As the mass shifts its position upwards the pressure upon it decreases, resulting in some expansion of the volume, some decrease in density, some increase in mobility. And the rising mass is hotter than the masses between which it is rising, unless the movement is at the same rate as the diffusion of heat. In proportion as the tensile stress is strong the upward movement will be pronounced, and may result in a flow of very dense, hot, viscous magma toward the surface of the earth. The greater the vertical distance, and the more rapid the rate of movement, the greater the difference in temperature between the magma and the inclosing mass.

That the eruption of rock magma is consequent upon the adjustment of accumulated stresses within the overlying rocks is indicated by the sequence of fractures and lava flows in the uppermost parts of the earth, and the opening of eras of great volcanic activity after profound orogenic movements have disturbed the comparatively quiet action of forces that have been

[1] A different conception of the act of intrusion of igneous rocks has been expressed by R. A. Daly, who states that the argument is based on the hypothesis of a solid crust floating on a liquid substratum; involves the extensive assimilation of schists and sediments by a primal gabbroid magma; and assumes that the liquid magma by heating and expanding adjacent portions of solid rock spalls off layers, or blocks, which descend and dissolve in the liquid, and by this process, termed magmatic stoping, progresses upward toward the surface of the earth. Mechanics of Igneous Intrusion, Am. Jour. Sci., vol. 15, 1903, p. 269; and vol. 16, pp. 107, 267. Also Abyssal Igneous Injection, etc., *ibid.*, vol. 22, 1906, pp. 195–216.

gradually shifting the stresses within the outer portion of the earth. The magnitude of the adjusting action is evinced by the extent of territory simultaneously affected; as for example, the initiation of volcanic action on a gigantic scale throughout western America at the end of Cretaceous time, after an enormous period of nearly uniform conditions of comparative quiet.

The eruptive impulse, or energy, causing the upward flow of magma, must originate in the expansion of the magma upon relief of pressure consequent upon the adjustment of stresses in the overlying mass, and from the expansive energy of dissolved gases. That the eruptive force is of the same order of magnitude as the stresses within the earth's crust is shown by the relatively small amount of material erupted upon the surface of the earth compared with the bulk of the whole; by the common intrusion of magma along fracture planes and along those of structural weakness, rather than at random through rock masses; and most conspicuously, by the evidence of equilibrium with the atmosphere maintained by lava in volcanic craters. Open vents are known to exist for centuries without great extrusion of rock magma, as at Stromboli. The stresses which produce condensation of volume in proportion to depth and the results of expansion of volume are, therefore, somewhat evenly balanced. The effect of expanding gases is shown in the explosive character of many eruptions, and the periodic character of all eruptions from open vents, or volcanoes. It must increase the volume of all magmas as pressure is relieved. Its effectiveness must increase with increase in the amount of gas in magma, which may result from diffusion of gas from greater depths of magma, and also from accession from adjacent rocks under favorable conditions.

Spasmodic eruption may follow sudden yielding of overlying rocks to long-continued stresses, as in the case of massive, or fissure, eruptions where there may have been no considerable explosive action of gas; or it may result from an accumulation of gas pressure sufficient to rupture overlying rock masses. Eruption is then accompanied by abundant evidence of explosion. Both causes undoubtedly operate together in most cases. Periodic eruption from volcanic craters probably follows the gradual accumulation of gas and heat within the magma, and acts in the same manner as the periodic eruption of water from geysers.

In so far as magmatic eruption is a result of volumetric expansion of the magma due to relief of pressure, the shrinkage of volume due to cooling will retard eruption, or eventually stop it. Crystallization will operate in the same direction. In proportion as eruption is due to expansion of dissolved gas, the escape of gas from magma, or the reduction of supply, will lessen the force of eruption, or eventually put an end to it. The supply of gas from great depths may be reduced by the gradual diffusion of whatever is in a position to be appreciably diffused; or the supply from rocks adjacent to intruded magma may be cut off by the closing of pores in these rocks through metamorphism; porous rocks becoming dense and almost impervious to gases. In these ways eruptive action initiated by crustal readjustment after continuing for variable periods may come to an end. Readjustment of stresses may recur from time to time in any region, either at such widely remote periods that the volcanic activities associated with each readjustment constitute distinct and separate periods; or at such frequent intervals that the results of several profound movements are combined to form a prolonged period of complex volcanic eruptions. Examples of various cases illustrating these relationships will be found in the descriptive part of this book, Volume II. Those eruptive actions which affect a wide range of territory and appear to have very deep-seated origin have been called REGIONAL. Those whose influence is confined to a narrow range, as about a particular volcano, are called LOCAL.

Independence of action at neighboring volcanoes, either as to period of eruption, volume of magma erupted, explosive, or quiet, character of action, or relative height of lava column in conduit of volcanoes, follows from local variation in the factors entering into the process of magma eruption, such as: the volume of magma involved in each conduit extending to profound depths; the shape of the conduit; the temperature of the magma; the rate of cooling; the amount of gas diffused in any given time; the character of surrounding rocks; and the stability of the rock mass as a complex whole. The chemical composition of the magma is also a factor involved in the activity of a particular volcano. But the composition of the magma is also a feature by which volcanoes may show independence. The occasion for

such differences in neighboring volcanoes is to be sought in variation in the differentiation of magmas during the course of their eruption from deep-seated sources to the surface of the earth. What such variations may be will be considered briefly.

Deep-seated magma by reason of the very gradual or slow changes that take place may be located where no differentiation can take place. Its composition remains constant. A sudden eruption from such depth to the surface, or near it, would bring up magma having the composition of the primitive magma. If the magma is located where differentiation may take place through differences of temperature, these changes will be slower the less the variations in temperature, that is, the greater the depth.

Magma that has been erupted to higher levels will experience greater differences of temperature in different parts, and will undergo greater differentiation in any given time when compared with deeper-seated magma, other things being equal. The size and shape of the fissure, or conduit, will modify the rate of differentiation. The temperature of adjacent rocks depends not only on their depth below the earth's surface, but to what extent they have been heated by the previous passage of magma. It follows from this that magma on its way to the earth's surface will experience different degrees of differentiation in different parts of its course through conduits, or fissures, variously shaped and branched.

**Complementary Rocks.** — A necessary result of the liquid differentiation of a mixed solution is that for any derived portion having a given composition there must be another portion, or portions, having complementary compositions, so that their combination will yield the original solution. No elements are lost, or eliminated, in such a differentiation. When differentiation results from the crystallization and solidification of a portion of a magma the case is different; there may remain but one differentiated liquid portion. In cases where large bodies of magma separate into two liquid portions having different compositions, these must occupy different parts of the conduit, or reservoir; and either one or the other may be erupted first, according to their relative positions and the location of the openings through which they are erupted. If a more feldspathic, or more siliceous,

portion be situated at the center of a reservoir, and a more ferromagnesian portion at the margin, then fissures tapping the center from directly above may draw off the more salic, central magma, while fissures at the margin of the reservoir may draw off the more femic magma. This is known to happen repeatedly at volcanic centers; dikes of such COMPLEMENTARY rocks being closely contemporaneous. Should two liquid portions having different compositions exist one above the other, in a reservoir, a fissure tapping it from above would be expected to draw off the upper portion before the lower. But this would not necessarily always be the case, for should the upper, and lighter, portion be the more viscous, the common case with rock magmas, and the lower portion the more liquid, it is possible for the more liquid magma to pass upward through the more viscous, owing to the greater internal friction in the more viscous liquid. A differential flow of the two portions would take place, resulting in the more liquid passing through the viscous, according to the size of the opening and the velocity of the flow.

Thus it may happen that complementary magmas may follow one another through the same fissures, producing composite dikes and sheets, which are of common occurrence in the region of Tertiary rocks in Great Britain, and occur to a less extent in other parts of the world.[1] In the Isle of Skye the two kinds of magma were erupted so near together in time that the second (salic) appears to have found the first (femic) still hot, and in some places possibly not completely crystallized or solidified.[2]

From the foregoing considerations it is clear that within one region of volcanic activity there may occur at the beginning of a period of eruptions vast outpourings, or explosions, of lavas having the composition of some deep-seated magma, which may be called the PARENT MAGMA in that region. This magma, occupying fissures and conduits of various sizes and shapes, undergoes differentiation, whose extent and rate vary with conditions in each part of the complex system of reservoirs, chiefly with respect to physical conditions, and the length of time it may remain within any part of the reservoir. In some places the magma enters branches from which it does not escape. Here it

[1] For bibliographic references see Harker, A. Memoir of the Geological Survey of the United Kingdom, Glasgow, 1904, pp. 198–200.

[2] *Ibid.*, pp. 169–234.

solidifies as intruded bodies, having various shapes and sizes, which have been called batholiths, laccoliths, bysmaliths, plugs, sheets, sills, dikes, veins, etc. Into these the magma may have entered at various temperatures in different instances, or it may have cooled to various temperatures before it came to rest at the end of its course. In these branches it may have been differentiated, or not, according to circumstances. Through some branches of the conduit, magma reaches the surface of the earth and flows out as lava, or explodes into dust and fragments. Clearly the composition of the magma reaching the surface will depend upon how much differentiation has taken place since it started from the place of the parent magma, also upon what portion of some higher reservoir it has been drawn from. It may happen that through one branch conduit salic magma continues to flow for some time and reaches the earth's surface in a series of small eruptions building a volcanic cone, while through another branch femic magma may flow and construct a volcano. Such differences exist in some neighboring volcanoes in many regions. Or the magma erupted at one volcano may vary in composition from time to time, at first having an intermediate, or average, composition, and then becoming more and more diverse until the last magmas erupted exhibit the most extreme differences of composition. While these events are taking place it may happen that a profound eruption may bring to the surface large volumes of magma like the parent magma, which must have existed unchanged while the smaller bodies of derived magmas were undergoing various degrees of differentiation. This eruption may be followed by long series of eruptions of variously modified derived magmas. And finally there may follow vast eruptions, of regional extent, of differentiated magmas from profound depth, which flowed from some large reservoir in which differentiation had been progressing more slowly than in the smaller, higher reservoirs or conduits tributary to individual volcanoes. Such a history is that of the region embracing the northwestern corner of Wyoming, with neighboring portions of Idaho and Montana,[1] and is no doubt that of many other volcanic regions.

[1] Iddings, J. P. Extrusive and Intrusive Rocks as Products of Magmatic Differentiation. Quar. Jour. Geol. Soc., London, 1896, vol. 52, pp. 606-617.

In a region of complex volcanic activities there can be no simple order of succession of magmas so far as their composition is concerned, since different kinds of magma may be issuing from neighboring volcanic craters. The simpler the acts of eruption, as in the series of fissure or massive eruptions in Nevada, Utah, and elsewhere, the more definite the succession from intermediate to alternate extremes of composition. And in localities where but part of a full cycle of eruptions may be exposed, or where differentiation may have been accomplished by partial crystallization and solidification of part of the magma reservoir, the composition of magmas at successive eruptions may vary in only one direction.

# CHAPTER VIII

## MODES OF OCCURRENCE OF IGNEOUS ROCKS

HAVING considered the composition, eruption, and solidification of rock magmas, it is in order to describe the ways in which they may appear as bodies of rock. These are in part of such a nature that the process of formation can be actually observed and investigated while in operation. In part they are such that their formation cannot be observed, but may be understood from the shapes of the rock bodies, and from their relations in space to adjacent rocks, and from other characteristics. To the first group belong extrusive eruptive rocks. The second embraces intrusive ones.

Extrusive rocks occur in the form of lava streams and surficial sheets, mud flows of tuff, heaps and beds of dust and stones, sometimes reckoned as tuff, sometimes are breccia; also as lapilli and bombs. Intrusive rocks assume the form of dikes, sheets or sills, laccoliths, and of other bodies. The chief characteristics of each of these modes of occurrence will be briefly described.

### EXTRUSIVE BODIES

**Lava Streams** (Stromen, coulées) **and Sheets** (Decken). Molten lavas reach the earth's surface through narrow openings, such as volcanic craters, usually at the summit of mountains, or through crevices of variable length in the sides of volcanic cones; or they may flow through immense fissures that traverse the country for miles and are without connection with any volcanic cone. In all cases the lavas may have the same characters and the resulting rocks may be petrographically identical. In any case the lavas may vary in liquidity, sometimes being highly viscous and stiff, at others being so liquid as to resemble water in their movement, as at Kilauea on Hawaii. Differences in liquidity may be due to three causes: First, differences in viscosity, due to differences in composition, the more siliceous

lavas being more viscous for a given temperature. Second, the temperature may differ in different cases, since it cannot be assumed that all lavas reach the earth's surface at one and the same temperature. Third, there may be a greater or less amount of dissolved gases in different lavas; the presence of gases greatly increasing the fluidity of the molten mass, as already explained.

From this it may be expected that the forms of solidified lava streams will vary greatly. The more liquid will move more rapidly and travel farther, becoming thinner. If poured out from a crater on a steep cone, they will form narrow streams, generally following channels of drainage, often continuing down the river valleys for many miles. The illustration, Fig. 1,

FIG. 1. KILAUEAN LAVA OF 1881 POURING OVER CLIFF. (Williams.)

shows the thin lava of Kilauea, erupted in 1881, pouring over a cliff into water. Some of these flows at Hawaii[1] are 30 miles in length, others in Iceland[2] are 50 miles long. Liquid magmas when poured out from large fissures flood the surrounding country with a broad sheet of lava, like the waters of a lake,

[1] Dana, J. D. Characteristics of Volcanoes, for facts regarding the volcanic phenomena of the Hawaiian Islands.

[2] Geikie, Text Book of Geology, 3d Ed., p. 222.

often very wide and comparatively thin. Occasionally such floods may be of enormous proportions, such as the basalts of Idaho, the Deccan basalts in India. The rhyolite lavas in the region of the Yellowstone Park[1] have spread over a territory of more than 2000 square miles, the southwestern limits of which are not known. The vast sheet is more than 2000 feet thick near its center. More viscous lavas will move more sluggishly, will travel shorter distances, and will pile themselves up into mounds, domes, and mountain masses.

There are structural characteristics of lava streams by which they may be identified, even if subsequently buried beneath other rocks. These differ somewhat according to the nature of the lava when flowing. The more viscous lavas crack on the surface, which solidifies before the central portion, and the fragments move over one another, producing a confusion of angular blocks sometimes called A-A. These occur both at the bottom and top of the sheet or stream. They merge into the central portion, which solidifies after the lava comes to rest and forms a massive rock. The rock fragments are scoriaceous and slag-like, often vesicular and carious. The massive portion may be dense or vesicular; the vesicles frequently flattened or elongated in the direction of the flow. It may even be pumiceous.

When the lava is more liquid there is less crust formed before it comes to rest, and consequently few if any fragments of slag in its upper and lower surfaces. The massive rock may then extend down to the bottom of the sheet. This is naturally accompanied by evidences of the heating of the underlying rocks when their nature is such as to be affected by it. The upper surface may then be rough with slag-like hummocks, or smooth with ropy contortions, called PAHOEHOE, Fig. 2; or it may be highly vesicular and pumiceous, according as there was little or much vapor to escape and expand the lava. The obsidian flow of Rocce Rosse on Lipari is but slightly inflated and vesicular on its upper surface. That at Obsidian Cliff in the Yellowstone Park had for its upper surface a white pumice.

The central mass of the flow may have a homogeneous tex-

[1] Hague, A. Am. Inst. Mining Eng. Trans., vol. 16, 1888, pp. 783–803, and Iddings, J. P., Quar. Jour. Geol. Soc., vol. 53, 1896, p. 613.

ture throughout, or it may be banded and streaked in layers parallel to the planes of flow. In some cases it may be finely laminated in the same planes. The former is more characteristic of less siliceous lavas, the latter of more siliceous lavas. The planes of flow may be folded and curved according to the

Fig 2. Kilauean Lava, Pahoehoe. (Cross, U. S. Geological Survey.)

movement of the lava. In very thick sheets the texture of the rock varies noticeably from the upper and lower surfaces toward the middle, especially in more siliceous lavas. The outer portions are more or less glassy, the inner parts more crystalline.

The cracking of the lava upon contraction is also characteristic and will be described more particularly later on. It pro-

duces cracks in parallel planes in some cases, generally near the surfaces of cooling and parallel to them; more often prismatic, or columnar, cracking which is nearly perpendicular to the cooling surfaces, the columns usually standing vertically and being in certain cases curved. There is generally a set of thicker columns at the bottom of the sheet and one of thinner columns in the upper part. This is often the case in basaltic lavas, but less often in rhyolitic ones.

Streams or sheets of lava conform to the surface of the country over which they flow, seeking the lower levels and accumulating in depressions or drainage channels. They catch up loose fragments of rocks over which they may flow, which become inclosed in the lower portion of the lava. And when they flow over fine sand or mud, this penetrates the crevices between the scoriaceous fragments. The presence and charter of such foreign material indicate the nature of the surface over which the lava flowed. This is well shown in the clay-like material filling interstices between blocks of basalt exposed on the Sicilian coast at Acicastello,[1] and in the calcareous mud filling cracks in a basalt sheet in the Connecticut valley.[2]

Occasionally lava in flowing separates into lumps or small masses that assume rounded forms and when solidified in a closely pressed aggregation have the appearance called PILLOW STRUCTURE.

Changes in the underlying rocks produced by heat from lava flows are seldom observed, for as already pointed out the surface of the lava is chilled and often solidified during the movement over these rocks, and it is seldom that highly heated, molten lava comes in contact with the rocks over which it flows. In some instances slight changes have been produced, but generally the heat is insufficient.

**Domes** (Kuppen).—When lava reaches the earth's surface in so viscous a condition that it does not flow easily, it will not spread far, but will pile itself up in a dome-shaped mass immediately over the orifice through which it was extruded. The form of the mass is not necessarily a symmetrical one,

[1] See Platania's account in The Southern Italian Volcanoes, ed. by Johnston-Lavis, Naples, 1891, p. 42.

[2] Emerson, B. K. Bulletin Geol. Soc. Am., vol. 8, 1897, p. 59.

indeed a symmetrical form must be the exception. The material being supplied from beneath the mass, it is evident that the surface after chilling and taking on the scoriaceous and slag-like characters of viscous lava streams, would be constantly stretched and cracked by the swelling of the molten mass within, so that the rising surface of the dome would present the appearance of an extrusion of fragmental blocks, as in the case of the eruption of the Isles of May at Santorin in 1866 described by Fouqué,[1] or in that of the island of rock that rose from the Lake of Ilopango, Salvador, on January 20, 1880.[2]

Subsequent erosion would remove the loose outer portion and modify the original shape of the body, leaving the massive central part, in which the planes of flow should be quite tortuous or more regularly disposed, according to the internal movement of the lava when molten. The lamination of such domes may be found in many positions for this reason, though often possessing a general parallelism to the outside of the dome.

Since the more siliceous lavas are generally the more viscous when extruded, they are oftener found in domes than the less siliceous ones. But the latter may in some cases be erupted in a highly viscous condition, so that domes of all kinds of lavas occur. Those of highly siliceous lavas are quite frequent. Domes of rhyolite and andesite occur in the Eureka district, Nevada.[3] Domes of phonolite, trachyte, and basalt occur in numerous localities in France, Germany, and Bohemia.

**The spine** of Mont Pelée, on Martinique, seems to have been an exceptional case of massive extrusion of highly viscous, if not solid, magma. It appeared after the first eruptions of the mountain in 1902, and rose to a height of about 800 feet above the platform of rocks forming the summit of the mountain. Its shape was that of a broad wedge tapering upward, and is shown in profile in Fig. 3 from a photograph by Dr. E. O. Hovey, taken in March, 1903, from the southern rim of the crater at a distance of about 600 meters. The side toward the crater was a nearly vertical cliff; the outer side had a smooth, steep

[1] Fouqué, F. Santorin et ses Éruptions, Paris, 1879, p. 71.
[2] Hague, A., and Iddings, J. P. Am. Jour. Sci. vol. 32, 1886, p. 29.
Russell, I. C. Volcanoes of North America, New York, 1897, p. 147.
[3] Hague, A. Monograph, 20, U. S. Geological Survey, 1892, p. 243.

Fig. 3. Spine of Mont Pelée, Martinique, March 26, 1903. (Hovey, American Museum of Natural History).

slope, as though planed off by slipping along the wall of the conduit. Explosions at the base of the vertical cliff gradually shattered the mass, which was reduced to a pile of loose blocks. Probably the highly viscous, vesicular, or pumiceous lava in the top of the conduit was forced out by the rise of magma beneath, and was sufficiently coherent in one portion to retain its form until broken to pieces by repeated explosions within the less viscous magma beneath.[1]

**Products of Explosion** (Tuff and Breccia). — Products of volcanic explosion in some instances form a very considerable part, possibly the whole, of the material erupted from certain centers of volcanic action. They are chiefly produced by the sudden expansion of gases inclosed in the molten magma, by far the greater part of which is derived from water. The material is of two kinds: (*a*) that formed from molten lava and (*b*) that produced by the fracturing of inclosing solid rocks.

(*a*) EXPLOSION OF MOLTEN LAVA, DUST, LAPILLI, BOMBS. — The explosion of gas within molten lava may drive it apart in minute shreds of glass and fragments of crystals when any were present in the lava before the explosion. The glass particles have the shape of pieces of broken pumice, and show that they are simply the result of pumiceous inflation which was so sudden and violent that the walls of the vesicles were ruptured and thrown into the air. The minuteness of the particles and the force of their expulsion may be so great that they may be driven as almost impalpable dust thousands of feet into the air, to be blown long distances by winds and deposited hundreds of miles away from their source. The most extreme case on record is that of the dust from Krakatoa,[2] which was thrown seventeen miles high and drifted completely around the earth, affecting the atmosphere so as to produce the unusual sunsets observed for months after the eruption.

As the size of material increases it consists of small pieces of lava, pumiceous, or vesicular, and scoriaceous, called LAPILLI.

[1] Hovey, E. O. Am. Jour. Sci., vol. 16, 1903, p. 269.

Lacroix, A. La Montagne Pelée et ses Éruptions. Académie des Sciences, Paris, 1904.

Heilprin, A. The Eruption of Pelée, Philadelphia, 1908.

[2] Geikie, A. Text Book of Geology, 3d ed., p. 212, also The Eruption of Krakatoa, a report of the Royal Society, 1888.

These range in size up to that of walnuts. Beyond this, larger lumps and masses of molten lava thrown out from craters are called BOMBS. They are irregularly ovoid and rounded, and quite rough or smooth externally according to the condition of the lava from which they were made. Usually they have a rather compact crust or shell, and a more or less vesicular or pumiceous center. The compact glassy shell probably results from the escape of the gas bubbles from the surface of the

FIG. 4. BREAD-CRUST BOMB, MONT PELÉE, 1902. (Hovey, American Museum of Natural History.)

bomb previous to the chilling of it during its flight through the air. One of the most remarkable forms of bombs was thrown from Vulcano, one of the Lipari volcanoes, in 1890. It is a gray glass of magma rich in silica, the outer shell consisting of compact glass, the interior being finely pumiceous. The shell has been cracked open by numerous gaping cracks, which have been spread by the contraction of the outer part and the expansion of the interior as sometimes happens in a loaf of bread. The name of BREAD-CRUST BOMBS has been given to them for this reason. They vary in size from a few inches to thirteen feet in diameter. They are very brittle and crack in pieces if dropped any distance. Originally they fell at least a thousand feet without breaking. They were at that time viscous and heated,

in some cases, to the temperature of melted silver. And it is probable that the compact glassy shell was sufficiently rigid to crack when the bomb struck the ground, after which the central portion expanded before solidifying, and yet the mass was not plastic enough to flatten when it struck. Similar bombs were thrown from Santorin in 1866 and from Mont Pelée[1] in 1902, one of the latter being shown in Fig. 4.

In some cases bombs consist of an aggregation of crystals, as of olivine or other minerals, which were present in the molten magma as segregations forming a solid mass. At the moment of explosion these masses were thrown out with more or less adhering lava. They are specially common in the Eifel, Germany. According to J. D. Dana[2] and Johnston-Lavis,[3] bomb-like lumps of lava may sometimes be formed by the rolling movement in the front and at the bottom of a lava stream. These are not properly bombs, but may better be called lava-balls, as suggested by Dana.

(*b*) EXPLOSION OF SOLID ROCKS. — Explosions in the crater of a volcano often shatter the cone and scatter fragments of all sizes over the surrounding country. The dust behaves the same as that formed from exploded lava, and may be as fine and be carried as far. Indeed, it is probable that much of the dust from volcanic explosions has originated in this way. The larger fragments are plainly seen to be angular pieces of rock whose petrographical character corresponds to whatever formed the cone of the volcano; compact crystalline rock or glassy kinds; and sometimes vesicular and pumiceous varieties. Fragments of all sizes are hurled into the air at once, the heavier masses falling first as a general rule, so that the layer formed by a particular explosion would have more of the larger pieces at the bottom. Such a crude assortment is sometimes observed in layers of breccia.

Large masses may be hurled long distances. A block weigh-

[1] Lacroix, A. La Montagne Pelée et ses Éruption. Académie des Sciences, Paris, 1904, pp. 522–526.

Hovey, E. O. Bulletin Amer. Mus. Nat. Hist., vol. 16, 1902, p. 333, and Am. Jour. Sci., vol. 14, 1902, p. 319.

[2] Dana, J. D. Characteristics of Volcanoes, New York, 1890, pp. 10 and 245.

[3] Johnston-Lavis, H. J. Proc. Geol. Assoc., London, vol. 9, No. 6, also Am. Jour. Sci., 1888, vol. 36, p. 103.

ing 200 tons is said to have been thrown nine miles by Cotopaxi.[1] In general the larger masses fall nearer the center of eruption, the most distant deposits consisting of the smallest particles. The accumulations of fine particles are called TUFF. Those composed of fragments and blocks of all sizes are BRECCIA, also called TUFF-BRECCIA and SUBAERIAL BRECCIA, in distinction from FLOW-BRECCIA produced by a lava flow crowded with rock fragments, and from a CRUSHED BRECCIA produced by the fracturing of a compact rock by pressure and displacement due to mountain-making processes. All of these breccias may resemble one another very closely when the rocks composing them are similar. It then requires a careful search into their mode of occurrence or character as geological bodies to distinguish between them.

Subaerial or tuff-breccias may be distinctly bedded in layers corresponding to periods of great explosive activity, and may cover vast tracts of country hundreds and thousands of square miles in area, and form deposits thousands of feet thick. Such are the great breccia formations of the Gallatin and Absaroka ranges in Montana and Wyoming,[2] those of the San Juan Mountains of Colorado,[3] the Cascade range of the Pacific coast of North America,[4] and the Andes.[5] The thickness of the breccias in some of these regions is 4000 feet and more. The layers may vary from a fraction of a foot to three or four feet in thickness, and frequently lie almost horizontally, or with a dip of only 5 degrees. This is true for breccias at considerable distances from a center of eruption. Near the center they dip at higher angles, increasing to 15, 20, or 30 degrees, where they form the slopes of a steep cone, as at Monte Somma, Vesuvius. Differences in the angle of slope on the surface of a cinder cone of dust and lapilli are well shown in the profile of such volcanoes as Fuji-yama, Japan, and Mayon in the Philippines, Fig. 5.

In the immediate vicinity of the center of great explosive

[1] D. Forbes. Geol. Mag., vol. 7, p. 320.

[2] Monograph 32, U. S. Geological Survey, 1899, Pt. 2, p. 215 and p. 269. Also Geologic Atlas of the United States, Livingston Folio, No. 1.

[3] Cross, W. *Ibid.*, Telluride Folio, No. 57, and Silverton Folio, No. 120.

[4] Hague, A., and Iddings, J. P. Am. Jour. Sci., vol. 26, 1883, pp. 222–235.

[5] Reiss, W., and Stübel, A. Reisen in Süd-Amerika, Berlin, 1892, and Jour. Geol., vol. 1, 1893, pp. 164–175.

action the breccias are not bedded, but are piled up in chaotic agglomeration. Such tumultuous aggregations of fragmental material are also found sometimes filling the necks of craters or of conduits through which eruptions have taken place. They are called VOLCANIC AGGLOMERATES. Instances of necks of volcanic agglomerates occurring within sedimentary rocks have

FIG. 5. MAYON VOLCANO, LUZON, PHILIPPINES. (Gannett, U. S. Geological Survey.)

been described by Geikie along the north of the Firth of Forth.[1] Large areas of agglomerate within volcanic breccia occur in the Absaroka range, Wyoming.

When the fragments have become more or less rounded through water action they form VOLCANIC CONGLOMERATE, which is often intercalated in beds with subaerial breccia. They indicate the presence of water about the flanks of the volcanoes. They have been described as of extensive occurrence in western

[1] Geikie, A. Trans. Roy. Soc. Edinburgh, vol. 29, 1879, pp. 437–518.

America, but it is probable that they actually form a small portion of the vast accumulations of volcanic breccia.

The material composing volcanic breccia may be quite uniform in petrographical character, or quite diverse, depending on the make-up of the masses which were blown to pieces. It may contain fragments of rocks not in themselves volcanic, such as sedimentary and metamorphic rocks. This is especially true of the products of the earliest eruptions at any center. Volcanic activity may commence in a new locality by the explosion of the crust of the earth, which may be limestone or sandstone, granite or schist. So that the first projectiles may be non-volcanic rocks. If the action stop after the first explosion there may result a crater within non-volcanic rocks as in the Eifel and elsewhere. Where volcanic action continues, true volcanic breccias become piled upon the first accumulation of non-volcanic material. Thus at one locality in the vicinity of Haystack Mountain, Montana, the lowest layer of andesitic breccia contains so much gneiss that the bottom of the deposit is almost wholly made up of angular fragments of gneiss, which rest upon the ancient surface of the country.

MUD FLOWS. — Dust and lapilli may become mixed with water and flow down the slope of a volcano in a stream resembling one of lava in its general form, but differing from it in petrographical character and in details recognizable with a microscope, when the fragmental character of the mud flow may be detected. They resemble tuffs deposited from showers except that the latter are often bedded. A distinction between the two may not always be made.

There are other flows of mud connected with mud-volcanoes where the material is not volcanic but usually of sedimentary origin. They are of small extent and of slight geological importance. Examples of these occur in the neighborhood of Baku on the Caspian Sea, and in the Crimea. Other instances are the small eruptions of mud and sand accompanying the earthquake at Charleston, S.C., in 1886.[1]

[1] Dutton, C. E. Ninth Ann. Rep. U. S. Geological Survey, 1889, p. 284.

## INTRUSIVE BODIES

The intrusion of molten lava between solid rocks is along planes of weakness where the rocks part more readily when subjected to stresses of various kinds. Planes of weakness may occur in any position, being controlled partly by the nature and structure of the rock traversed, partly by the direction of the stress.[1] The form or shape of the body of lava after it has been solidified depends mainly on the nature of the crack or fissure penetrated by it and also on the character of the intrusion, whether gradual or sudden and whether accompanied by explosions. Various fórms of intrusive bodies have been named according to their shape or position and relation to surrounding rocks.[2]

**Dikes and Veins** (Gangen, filons). — When the fissure or crack is vertical or nearly so, the intruded body is a DIKE or VEIN. Its sides or walls are nearly parallel to one another, and its thickness is small compared with its dimensions in the plane of the fissure. The size of dikes varies greatly. They range from less than a foot in thickness, when they are more usually called veins, to many feet in thickness; and their length may be reckoned in feet or in miles. Certain dikes in Great Britain have been traced for 60 and even 90 miles. They are found traversing all kinds of rocks, including crystalline schists, sedimentary formations, and igneous terranes, both massive and fragmental. They may lie in groups with parallel trends, or they may intersect one another at all angles. In the vicinity of volcanic centers, especially in the body of a volcano, they have a general radial arrangement, diverging outward from the center of eruptive activity. This has been shown to be the case at Etna,[3] and in numerous localities in Montana[4] and Wyoming.[5]

Dikes may branch or fork into several parts more or less

[1] See the discussion of this subject by C. R. Van Hise in Sixteenth Ann. Rep. U. S. Geological Survey, 1895, pp. 571–844.

[2] For a discussion of the classification of bodies of intrusive rock see Daly, R. A., Jour. Geol., vol. 13, 1905, pp. 485–508.

[3] von Waltershausen, S., and von Lasaulx. Der Ætna, Leipzig, 1880.

[4] Pirsson, L. V. Am. Jour. Sci., vol. 50, 1895, p. 120. See also Geological Atlas of the United States, Folio 1, Livingston Quadrangle.

[5] Monograph 32, part 2, U. S. Geological Survey, 1899, p. 224 *et seq.*

parallel to one another, or they may send off arms at any angle. Offshoots from larger bodies of intrusive rock are called APOPHYSES. Dikes may wedge out gradually or rapidly, or end abruptly. Veins of smaller dimensions may grade into those with almost microscopic thinness, Fig. 6. When they traverse a body of intrusive rock and are comparatively coarse-grained, so that they appear to have penetrated it soon after consolidation and while it was still highly heated, they are called CONTEMPORANEOUS

FIG. 6. DIKE, VEINS, AND APOPHYSES. (Bastin, U. S. Geological Survey.)

VEINS, as already described. Dikes may reach the earth's surface and be connected with extrusive bodies of lava, or they may stop short of the surface. They may exist at different depths beneath the surface, in some cases being very deep-seated. When two dikes intersect, the body of the younger traverses the older; the relative period of intrusion of the two magmas being in this way established.

The character of the rock constituting dikes may be anything from that of a surface lava to that of a coarsely crystallized massive rock. It may be vesicular or porous when occurring

near the earth's surface, the vesicles usually being flattened parallel to the walls of the dike; or it may be compact and aphanitic or glassy. Often the margins or surfaces of the dike rock are finer grained than the central portion, or they may be glassy. All degrees of crystallization, from the smallest to the largest, may be found in dikes of like thickness. The color, texture, and composition sometimes vary from the center to the sides of the dike, owing to different rates of cooling, of crystallization, or to a molecular differentiation of the molten magma after its intrusion. Naturally, igneous rocks of all kinds of chemical composition may occur in dikes. Dike rocks when fine-grained to glassy are often cracked into plates parallel to the walls, or into prisms that stand perpendicular to the walls, and lie nearly horizontal. In thick dikes the direction of the cracks is not always so definite. In glassy dike rocks a spheroidal parting is sometimes developed. Coarse-grained dike rocks are oftener free from regular jointing of any particular kind, being massive and compact.

Sandstone Dikes and Veins.—There are dikes and veins of sand rock that resemble in general appearance dikes and veins of igneous rocks. They are intrusive or eruptive rocks in the sense that they have been forced into crevices or fissures within solid rocks. Microscopic examination proves that they consist of sand particles, and that they are clastic rocks, which while plastic and not yet indurated have been intruded as quick sands into fissures. Their true character often is only detected with a microscope. They have been found in California[1] and in Nebraska.[2] Veins of sandstone, some of very great size, occur traversing granite in Colorado.[3]

**Stocks, Necks, Cores** (Stöcke). — More or less vertical pipes, through which molten magma has been forced, when filled with solidified lava become STOCKS, NECKS, or CORES. Their shape is seldom regular, and depends upon the circumstances of their formation. They may be produced by the explosion of gases, analogous to the small holes made in stone by high explosives in the experiments of Daubrée.[4] In this case their section may be crudely circular, and they may be filled with fragments of the

[1] Diller, J. S. Geol. Soc. Am. Bulletin, vol. 1, 1890, pp. 411–442.

[2] Hay, R. *Ibid.*, vol. 3, 1892, pp. 50–55.

[3] Cross, W. *Ibid.*, vol. 5, 1894, pp. 225–230; also Crosby, W. O., Bulletin Essex Inst., vol. 27, 1895, pp. 113–147.

[4] Daubrée, A. Comptes Rendus, 1890, vols. 111, 112, 113; and Bulletin Soc. Géol. France, vol. 19, 1891, p. 313.

surrounding wall rocks together with igneous material as in the case of the volcanic necks near Edinburgh.[1] Or they may have been filled with molten magma following the explosion. Such necks may traverse solid rocks without apparent connection with fissuring. More often they are situated along the plane of a fissure, and occur where explosions, or repeated fracturing, have permitted the wall rock to be carried away by the currents of magma, thus widening the fissure at this place. They may occur at the intersection of successive fissurings, as at Electric Peak, Yellowstone Park,[2] and become the conduit for a prolonged series of eruptions. In such cases their shape is quite irregular, more or less lenticular in cross section, and split in branches which run into apophyses and dikes. They may be more nearly round when in the center of a volcanic cone, but branch out in all directions, passing into dikes that have from time to time broken away from the central conduit. When they penetrate sedimentary strata their form may be still farther complicated by the branching out of both dikes and horizontal sheets, as in the Crazy Mountains, Montana.[3] Their diameter may be several hundred feet or several miles. That in the Crazy Mountains is six miles in one direction by three in another.

The igneous rock constituting a stock may be all of one kind and belong to one mass of molten magma which was intruded at one time, or it may be composed of different kinds which represent different magmas that were intruded in a succession of eruptions, as in the great core in the Crazy Mountains, Montana, and in that on Crandall Creek, northeast of the Yellowstone Park.[4]

These traverse one another as irregularly shaped bodies or as dikes or veins. Sometimes the mass forming one body of intruded magma may vary in composition and texture in different parts of the body, the changes in composition being due to chemical differentiation in the magma before its intrusion, as at Yogo Peak, Little Belt Mountains, Montana.[5] The rock

[1] Geikie, A. Trans. Roy. Soc., Edinburgh, vol. 29, 1879, pp. 437–518.

[2] Monograph 32, U. S. Geological Survey, 1899, Pt. 2, p. 89 *et seq.*, and Twelfth Ann. Rep. U. S. Geological Survey, 1892, pp. 569–664.

[3] Geological Atlas, Folio 1, Livingston Quadrangle, U. S. Geological Survey.

[4] Monograph 32, *ibid.*, p. 246.

[5] Weed, W. H., and Pirsson, L. V. Am. Jour. Sci., vol. 50, pp. 467–479.

forming stocks may be very coarse grain or of any intermediate texture to extremely fine-grained. They are more commonly coarse-grained. The more crystallized stock rocks seldom exhibit definite parting or cracking such as columnar or platy parting. Their joints are such as arise from dynamical stresses accompanying pressure. In stock-like intrusions, however, which have solidified near the earth's surface, and whose petrographical characters are nearly those of extrusive rocks, columnar or platy parting may be developed.

**Intrusive Sheets, Sills** (Intrusive Lager, Lagergänge, in part).—When the planes of weakness within the rocks invaded by molten magmas occur along bedding planes of sedimentary strata or of igneous rocks, the magma is intruded in sheets between the beds, raising the superincumbent strata to a variable extent, producing thin or thick sheets of intrusive rock. The fracture may cross the strata to another horizon along which it may continue for some distance. Thus the sheet of igneous rock may break across the beds of sedimentary rock as a dike and continue as a sheet at some other horizon. Usually the transgression is from a lower to a higher horizon, and with the advance of the sheet from its source there is generally a thinning out. From these characters the course of the lava during its eruption may be determined. Intrusive sheets may be less than a foot thick or several hundred feet thick. They sometimes extend many miles. The celebrated Whin Sill of the north of England has been traced for 60 or 70 miles,[1] its thickness ranging from 20 to 150 feet. The great intrusive sheet of doleritic rock that forms the Palisades on the Hudson River opposite New York City is hundreds of feet thick, and has been traced for about 100 miles in a north and south direction.[2] Intrusive sheets occasionally send offshoots into the overlying rocks and into those beneath them.

The rocks composing intrusive sheets are compact and generally very fine-grained or aphanitic. They seldom exhibit columnar or platy parting, but are usually massive, without regular systems of cracks. They are sometimes darker colored and denser along

[1] Teall, J. J. H. British Petrography, London, 1884, p. 207; and Quar. Jour. Geol. Soc. London, 1877, vol. 33, p. 406.

[2] Lewis, J. V. Am. Jour. Sci., vol. 26, 1908, pp. 155–162; and Ann. Rep. Geological Survey New Jersey, 1907, pp. 97–167.

the upper and lower surfaces near the contact with the inclosing strata, but seldom vary much in grain across the sheet. An arrangement of the minerals parallel to the surface of the sheet is occasionally observed. Very rarely there may be a differentiation of the magma after its intrusion, as in the rock of the Palisades, New Jersey.

**Laccoliths.**[1] — When the lifting of the strata overlying an intruded sheet of magma becomes so localized as to raise them in a dome, or arch, above the igneous rock, the mass solidifies as a LACCOLITH, the bottom surface being nearly horizontal, Fig. 7.

FIG. 7. IDEAL CROSS SECTION OF A LACCOLITH WITH ACCOMPANYING SHEETS AND DIKES. (Gilbert.)

A laccolith differs from an intrusive sheet in having superincumbent strata arch over it, instead of lying nearly horizontal, or at least being parallel to the underlying strata. Laccoliths are not so extensive laterally as sheets, and are generally much thicker. The arching of the overlying strata is sometimes accompanied by faulting and dislocation, which, if it should extend all around the area, would permit the upper block of strata to be forced upward, giving rise to a plug of igneous rock or bysmalith. The two forms of intrusion grade into one another, the bysmalith being the extreme in vertical dimension; a sheet or sill, which also grades into a laccolith, being the extreme in lateral dimension. The thickness of laccoliths ranges from less than a hundred feet to several thousand feet; and their diameters range from a few hundred yards to several miles. The rock composing a lac-

[1] For descriptions of laccoliths see Gilbert, G. K., U. S. Geogr and Geol. Survey of the Rocky Mountain Region, Washington, 1877; also Cross, W., Fourteenth Ann. Rep. U. S. Geological Survey, 1893, pp. 165–241.

colith usually represents one body of magma intruded at one time. It may be homogeneous in composition and texture, with slight variations at the margin, becoming denser, darker and finer-grained at the surface of the mass. Such laccoliths are generally very fine-grained, as in the Henry Mountains, Utah, and in Colorado. Others vary in composition to a marked degree and are comparatively coarse-grained. The marginal portion may be dark and low in silica, or rich in ferromagnesian minerals. The variations are the result of differentiation *in situ*, as at Square Butte, Highwood Mountains, Montana.[1] Columnar structure or rude prismatic parting is sometimes developed, the columns standing vertically. Upon the removal of the marginal portion of a columnar laccolith, the central part remains standing, often rising like a columnar monument above the surrounding country. Platy parting parallel to the upper surface of the laccolith may also be developed, as at Square Butte. In many cases the laccolith rock possesses no definite system of cracks, but separates into irregular slabs and fragments, as in the Indian Creek laccolith in the Yellowstone Park.

5. **Bysmaliths.**[2] (Volcanic plugs.) — Intrusions of magma that have been forced nearly vertically through other rocks, and may or may not have reached the earth's surface, solidify in the form of plugs. In case the lava has reached the surface of the earth, they do not differ from volcanic necks. As already remarked, they are like laccoliths exaggerated in the vertical dimension and accompanied by nearly vertical faulting of the containing rocks. The intrusion took place as one act, and the superincumbent rocks were lifted at one time. This constitutes a distinction between bysmaliths and stocks, the latter frequently representing the filling of a channel through which successive eruptions of magma have taken place, as through the conduit of a volcano. An example of bysmalith is found in the intrusive mass at the southern end of the Gallatin Mountains, Yellowstone National Park, which embraces Mount Holmes,[3] and is shown in section in Fig. 8.

6. **Batholiths.** — There are bodies of intrusive rocks that are quite irregular in shape and traverse other rocks without definite

[1] Weed, W. H., and Pirsson, L. V. Bulletin Geol. Soc. Am., vol. 6, pp. 389–422.

[2] Iddings, J. P. Bysmaliths, Jour. Geol., vol. 6, 1898, pp. 704–710.

[3] Monograph. 32, U. S. Geological Survey, 1899, p. 16.

relation to their position or structure. They are nearer stocks in their mode of occurrence than other forms of intrusive bodies. To them the term batholith has been applied by some American geologists, although the word was originally employed in a different sense by Suess. Their structure and petrographical characters are not different from those met with in stocks.

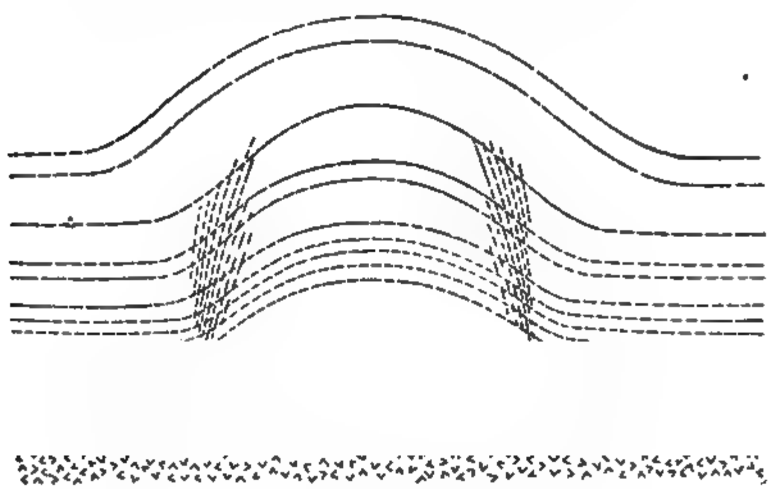


FIG. 8. IDEAL SECTION OF HOLMES BYSMALITH.

7. CONTACT PHENOMENA. — Many intrusive bodies have affected the rocks immediately in contact with them, changing their color, or texture, and crystallization, and causing special kinds of minerals to be developed in them. This *contact metamorphism* is very slight in the case of most intrusive sheets and laccoliths, and of many dikes. It is strongly marked around stocks that have served as the conduits through which volcanic eruptions have taken place, and in places where dikes are numerous and close together. It is most developed alongside of large bodies of coarse-grained rocks. It is the surest means by which the relative age of adjacent rocks may be determined.

All intrusive bodies may send out larger or smaller offshoots into the inclosing rocks, which is one of the means by which they may be distinguished from extrusive bodies. They are not accompanied by tuff or other fragmental material, except in the case of

agglomerates filling necks, and such breccias as may be formed by the fracturing of inclosing rocks, or of earlier intrusions, and the permeation of this breccia by later molten magma. Massive intrusive rocks may be converted into crushed breccias by great pressure as already mentioned.

Intrusive rocks are not scoriaceous, and are only vesicular when occurring in dikes near the earth's surface. In most cases intrusive rocks are compact and massive as though consolidated under great pressure.

## STRUCTURE OF IGNEOUS ROCKS

The term STRUCTURE is here applied to those large features of rock bodies which have been produced by cracking, by fracturing and aggregation, or which may be brought about by erosion. It is commonly used by many petrographers for what has already been described as texture and fabric.

Most rock structures result from special kinds of cracking, or jointing, in the body of the rock, and are of two classes: those due to shrinking, or contraction, within the mass, and those caused by shearing from pressures acting upon the mass from without. The latter properly belong to changes included under metamorphism, but are so closely allied to the first in the nature of the forms produced that they should at least be mentioned in this connection.

Cracking, or parting, of a rock, due to contraction upon cooling after solidification, happens when the tensile stress exceeds the resistance due to molecular cohesion of the mineral constituents. That it happens after solidification is shown by the dividing of crystals lying in the path of fracture, which are cut sharply across, the severed parts remaining firmly fixed in their matrix whether this be crystallized rock or glass. The position of the plane of fracture is normal to the direction of maximum stress at any point. The arrangement and form of fracture planes must depend upon the distribution of stresses in the contracting mass. As these vary with conditions of cooling, so must the character of the cracking. The resulting structures are of three kinds: SPHEROIDAL, PRISMATIC or COLUMNAR, and TABULAR or PLATY; according as the contraction and resistance are nearly uniform in all

directions in the rock; are greatest in various directions in a plane; or are greatest in one direction only.

**Spheroidal Parting or Structure.** — If within a homogeneous solid the rate of cooling is so gradual that there results a uniform contraction acting toward any point within the mass, the effect would correspond to the equal shortening of the radii of a sphere of such a body. If the resistance to contraction is uniform, when cracking takes place the plane of fracture will be normal

Fig. 9. Spheroidal Parting in Basalt. (Gilbert, U. S. Geological Survey.)

to the radii, that is, spherical. There may result, then, concentric spherical cracks. If any cause operates to diminish or increase either the tensile stress or the resistance in a given direction the resulting fractures will be no longer spheroidal but ellipsoidal. In a rock mass such a factor may be the action of gravity operating vertically.

Spheroidal parting is less common than other kinds, but occurs both in extrusive and in intrusive rocks. The rock

cracks with spheroidal planes, several of which are concentric about a compact nucleus of rock, producing shells one or more inches thick, sometimes thinner. The spheroidal cracks are irregularly disposed through the body of the rock, with angular fragments between. Their shapes are seldom spherical, but oftener ellipsoidal. The diameter of the spheroid may be a few inches, or several feet.

The spheroidal cracks are frequently more pronounced in weathered and decomposed rocks; in which case they may be sometimes due to the unequal expansion of the rock through the partial hydration of its outer portion, and also to alternate changes of temperature when exposed to weathering.

FIG. 10. PERLITIC STRUCTURE IN RHYOLITE.

Spheroidal cracking usually accompanies prismatic structure. It is found in rocks of various compositions and textures, such as basalt, trachyte, andesite, rhyolite, porphyries, and granite. It is well developed in the basalt near Cascades, Oregon, Fig. 9; in that of the so-called Cheese-grotto, near Bertrich in the Eifel; and in the trachytic pitchstone on the island of Ponza. It is developed to some extent in the large columns of basalt in O'Rourke's quarry, Orange Mountain, N. J.

PERLITIC STRUCTURE, which occurs in glassy rocks, is caused by the cracking of the glass into small spheroids with imbricated shells, like the parts of an onion, Fig. 10. The small spheres of glass resemble pearls. The structure is the same as that of spheroidal parting, and is due to the same cause, the contraction of the mass.

**Prismatic Parting or Columnar Structure.**[1] — When a homogeneous solid cools from a plane surface at such a rate that there is an appreciable difference in the temperature of successive

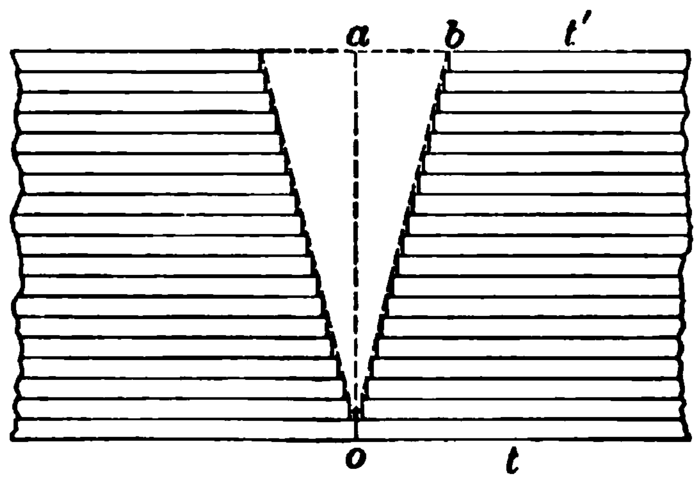



FIG. 11.

parts from the surface inward, and the cooling is uniform throughout the surface, then the stresses due to contraction of the mass will be uniformly distributed through the surface layer of the solid, and will be greater than any contractional stresses acting at an angle to the surface. For the contraction in the surface layer is greater than that in other directions, since the surface is the coolest portion of the rock. In like manner the contraction will be uniformly distributed, and slightly less in successive layers parallel to the surface layer. As contraction progresses the limit of cohesion for the rock mass will be reached first in the surface layer; and as the maximum stress is in this layer, parallel to the surface, the rupture will be in a plane normal to the surface of the rock. As the limit of cohesion is reached in each successive layer from the surface inward, the crack will advance inward normal to the surface.

The condition of the solid may be represented diagrammatically by Fig. 11, which is evidently that of a case of tangential shear in which half the con-

[1] Scrope, G. P., Volcanos, London, 1872. Mallet, R., Proc. Roy. Soc., London, 1875. Bonney, T. G., Quar. Jour. Geol. Soc., London, vol. 32, p. 140. Iddings, J. P., Am. Jour. Sci., vol. 31, 1886, pp. 321–331.

**traction is $\frac{ab}{ao} = \tan \alpha$, the measure of shear in the rock, when *ao* is the distance from the surface to the layer of equilibrium between tensile stress and cohesion. Now the limit of possible shear is a function of the rigidity of a solid, that is, there is a maximum value for $\tan \alpha$, beyond which a solid may not be stressed without rupture. This coefficient of rigidity, $n = \frac{f}{\tan \alpha}$, must be a physical characteristic of each kind of rock. The angle $\alpha$ depends upon the amount of contraction, *ab*, for difference of temperatures, $t$ and $t'$, at the**

FIG. 12.

**layer of equilibrium and at the surface of the mass, and also upon the depth, *ao*, at which the temperature is that of equilibrium, $t$. The more rapid the cooling, the steeper the temperature gradient, the shorter the distance between the surface and the layer whose temperature is $t$. That is, the more rapid the cooling, the larger the angle $\alpha$ would become if only one fracture took place in the mass. When, however, the angle $\alpha$ reaches its maximum, according to the rigidity of the rock, there can be no more shearing of the mass within the limit of cohesion, and further contraction must occasion another rupture at such distance from the first as the rigidity and temperature gradient of the cooling rock demand. From this it follows that the more rapid the cooling in any given rock, the closer together will be the cracks due to shrinkage.**

If two sides of a body of igneous rock cool at different rates, as the top and bottom of a lava sheet, the shrinkage cracks will be closer together in the upper portion than in the lower, as shown in Fig. 13. If the center of a dike cools more gradually than the surfaces, the shrinkage cracks in the central portion will be farther apart than those in the outer portions.

When the rate of cooling is not the same at all points on the surface of a rock mass, but varies from place to place, as through

convection currents in the atmosphere over a lava flow, then the direction of the planes of fracture will not continue normal to the cooling surface.

For the layers, or planes, of like contractional stresses will not proceed parallel to the surface plane, as indicated in Fig. 12, in which the shaded portion represents the variation in rates of cooling, the maximum being at *c*. Cracking will begin at *c*, and be closer together than at *a*. At the end of a given time the isothermal plane at which cracking takes place will be farther from the surface below *c* than below *a*. It will curve downward, and the fractures normal to it will diverge and curve, resulting in curving cracks, diverging from the cooling surface. This is well shown in the basalt in O'Rourke's quarry and elsewhere on Orange Mountain, N.J., Fig. 13.

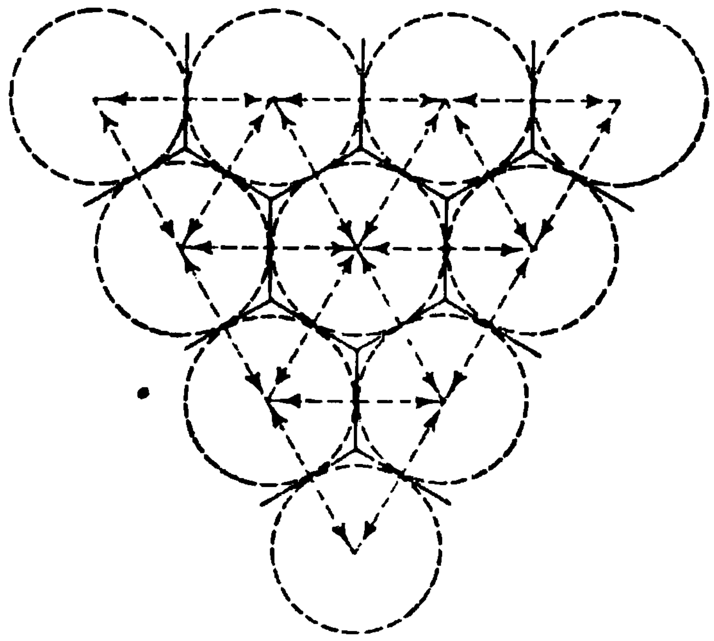


FIG. 14.

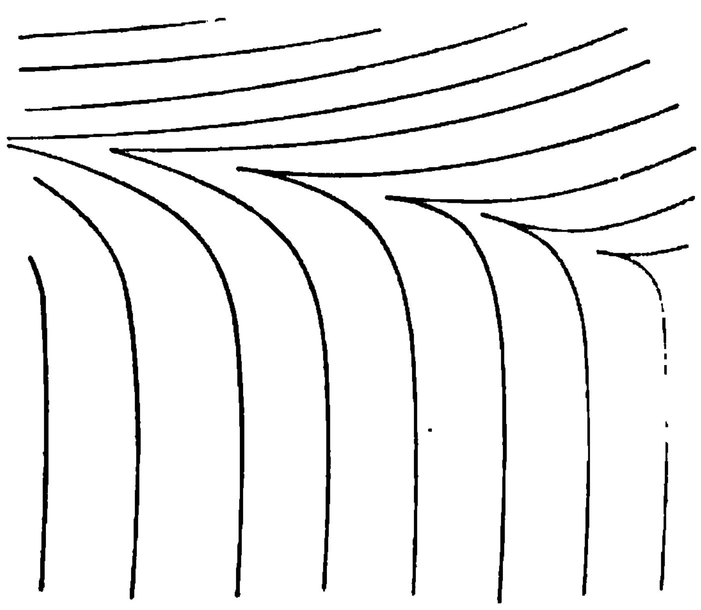


FIG. 15.

The discussion so far has had to do with the direction of cracking in a plane normal to the surface of the rock body. But in a homogeneous mass cooling uniformly over a plane surface contraction will exert itself equally in all directions, and at the instant of rupture will act toward centers equally spaced throughout the plane of the surface. Their distance apart is controlled by the rigidity of the mass and the rate of cooling. Points equally spaced in a plane are at the corners of equilateral triangles, Fig. 14, the lines connecting them being those of maximum tensile stress in the surface layer of the rock. Fracture will, therefore, start at right angles to these lines, and the resultant system of cracks will be hexagonal. Inward progress of these cracks divides the mass into six-sided prisms or columns. When the stresses are not uniformly distributed, owing

to lack of perfect homogeneity in the mass or in the cooling, the centers of contraction will not be uniformly spaced, and the resulting prisms will not be regularly hexagonal, but may have different numbers of sides, and these will be of different lengths. Adjacent prisms may have four, five or six sides, occasionally more.

When two systems of prismatic cracks approach each other at an inclination, the direction of advance of each system is

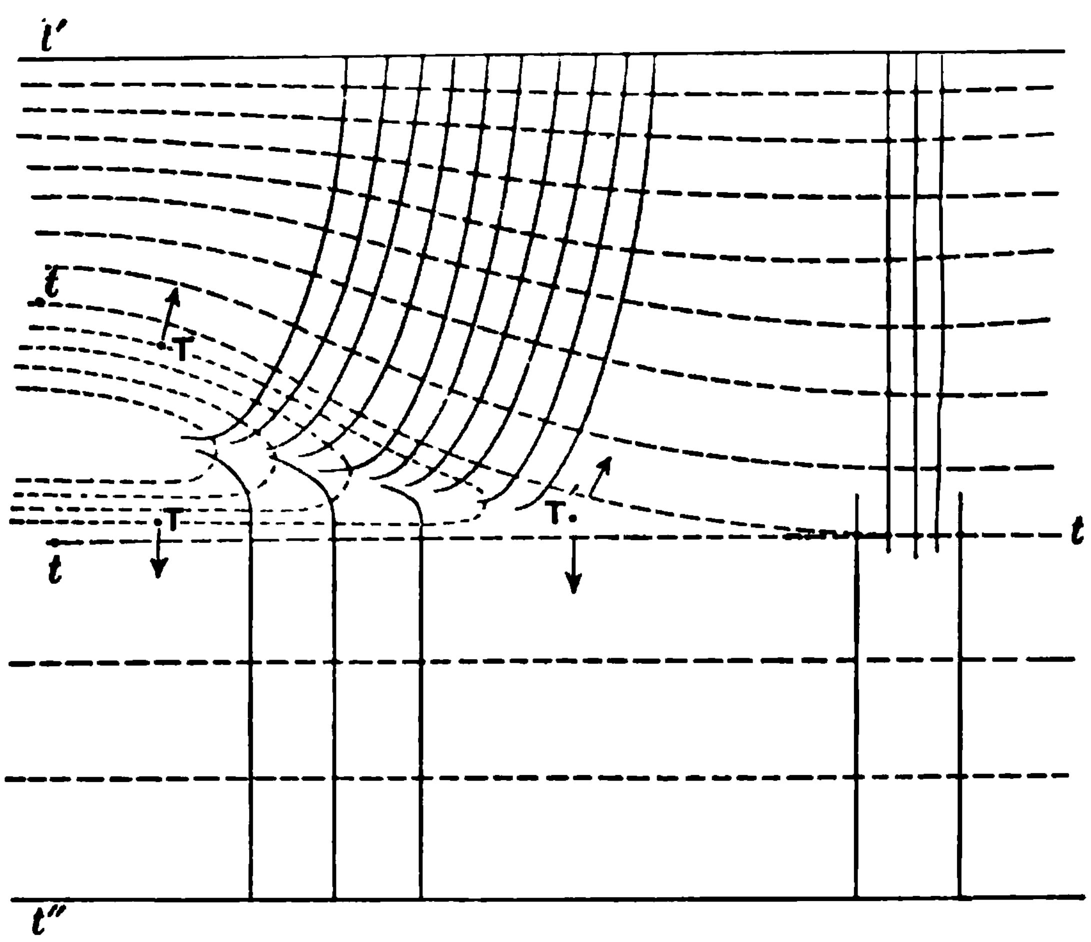



Fig. 16.

changed in such a manner that the prisms curve so as to meet at a more acute angle, as shown in Fig. 15, and in the pictures of the columnar structure in O'Rourke's quarry, Figs. 13 and 17. The cause is found in a change in the rate of cooling in the rock near the juncture of two such systems of prismatic fractures.

In Fig. 16 the isothermal lines of cooling are shown, the lower system parallel to the bottom surface of the rock, the upper system curved downward. The temperature $t$ is that at which fracture begins. It is evident that just beyond the isotherms $t$ there must be those whose temperature is $T = t + a$, the heat from which diffuses at certain rates across the isotherm $t$ above and $t$ below, respectively. But at $T'$, where the isotherms, $tt$, are equally distant, heat diffuses in both directions as indicated by the arrows. This part of the rock must be cooler than at $T$ and $T$, and the isotherm of $T$ must be curved from those of $t$, $t$, as indicated in the figure. As cooling progresses the fractur-

FIG. 17. TAPERING COLUMNS OF BASALT, ORANGE MOUNTAIN, N.J.

ing temperature *t* will eventually occupy this position, and the prismatic cracking will follow the normals to these isotherms. The result will be that prisms meeting at an inclination will bend more or less abruptly, and taper out as they come together. Examples of this phase of prismatic structure were well exposed in O'Rourke's quarry at one time, Figs. 13 and 17.

Columnar structure, or prismatic parting, is very common in bodies of extruded rock, and in many intrusive ones. The prisms, or columns, are usually perpendicular to the cooling surface when the cooling has been uniform, as already said. But groups of diverging and curved columns are frequently developed just below the upper surface of extrusive sheets of lava, while those developed from the bottom of the sheets are normal to it and straight; and as the cooling is more rapid from the upper surface, the columns in the upper portion of a sheet are usually much smaller than those at the bottom.

In dikes of igneous rock, solidified at no great depth, prismatic cracking is developed in the same manner, but the cooling along both sides of the dike is so nearly the same that in most narrow dikes the prisms extend straight from side to side, and are perpendicular to the walls. They are therefore usually horizontal.

The sides of the prisms may be quite straight and comparatively smooth, or they may be uneven and crooked, like many starch prisms. Sometimes their surface is marked by bands across the column, resembling crude chiselings, as in the quarry on Orange Mountain. No satisfactory cause for them has been suggested. The size of the prisms may be anything, from a diameter of an inch and less to one of twenty feet, and from a length of several inches to one of 80 or 100, and even 200, feet. The larger prisms are called columns.

They are most commonly developed in basaltic lavas, the best examples being those of the Giant's Causeway, the Cave of Staffa, the basalts of the Auvergne, those through which the Snake River has cut its canyon in Idaho, and those at the Dalles of the Columbia, in Oregon. They are finely developed in rhyolitic lavas in the Yellowstone Park, especially in the obsidian at Obsidian Cliff,[1] Fig. 18, and in the canyon of the Yellowstone River near Broad Creek. They also occur in all

[1] Monograph 32, U. S. Geological Survey, 1899, Pt. 2, p. 359, *et seq.*

kinds of lavas, andesites, trachytes, phonolites, etc., and to some extent in massive tuffs.

In the more siliceous lavas platy parting is more common than prismatic, the reason for which will be suggested later on. In massive rocks that have cooled very slowly and have solidified under great pressure the cracks are relatively far apart

FIG. 18. COLUMNAR STRUCTURE AT OBSIDIAN CLIFF, YELLOWSTONE NATIONAL PARK.

and no marked columnar structure is developed. This is true of the more granular rocks, such as granite, though columnar structure sometimes occurs in this rock, as along the coast of Cornwall.

Columns of igneous rock are sometimes divided by transverse joints at more or less regular intervals, or they may be continuous for great lengths. The cross cracks are often curved so as to produce a cup-shaped joint, which is probably related to

spheroidal cracking. Rarely columns of basalt consist of spheroids set one upon another, as in the Cheese-grotto near Bertrich in the Eifel. In andesite of Stenzelberg, Siebengebierge, the columns are cylindrical.

Columnar cracking is also produced by shrinkage due to the loss of water from a rock mass caused by evaporation or by baking, hence it may be developed in sedimentary rocks as a result of contact metamorphism.

**Tabular or platy parting** occurs very frequently in bodies of more siliceous lavas, and also in intrusive rocks of all kinds, the planes of cracking being parallel to the cooling surface, that is, exactly at right angles to those producing columns, and, since they are both due to surface cooling, their difference of position must depend upon other factors. Tabular parting frequently occurs just below the upper surface of a lava sheet, extending a short distance downward and being replaced by columnar cracking at right angles to it, as at Obsidian Cliff. In some cases it occurs throughout the mass, as in many sheets of rhyolite, and in some of andesite. Intrusive basalts at Eureka, Nev., are cracked into thin plates parallel to the curved wall of contact between the basalt and rhyolitic tuff. Dike rocks are often cracked in plates near the sides, while the central part is columnar. It is very common in phonolite and trachyte. There is another kind of platy parting which conforms with the lamination of a rock, and is specially characteristic of highly siliceous lavas, and it is probable that the two are not always distinguishable from one another.

Platy parting of the first kind, while taking place in apparently homogeneous rock masses, is undoubtedly due to actual physical differences in the mass. When the surface of a magma is rapidly cooled, the outer layer is cooled more rapidly than that just within, and this more rapidly than the next, and so on. That is, the rate of cooling is slower and slower from the outside inward. And the rate of change will be greater as the conductivity of the mass is poorer. If the outside be chilled so as to solidify as glass, its contraction will not be as great as that portion of the lava which cools slow enough to crystallize, since the condensation is greatest in the crystal phase. Hence the direction of maximum stress of contraction will be normal

to the surface in that portion of the mass where such physical differences exist, and the plane of rupture will be at right angles to this stress, that is, parallel to the cooling surface. This explains platy parting near the surface of extrusive sheets, and near the walls of intruded bodies, columnar cracking taking place where the mass is physically more uniform, Fig. 18. It also explains its more frequent occurrence in the more siliceous lavas, for variations in the degree of crystallization are more common, and the transition from glassy margin to crystalline interior extends through a broader zone than in the less siliceous rocks.

The second kind of platy parting is due to alternations of more or less crystalline and glassy layers caused by the spreading out of the molten magma while flowing, the magma being irregularly charged with water and other gases, which promote crystallization. It depends on a lack of physical and chemical homogeneity in the molten magma, and this occurs more frequently in the less liquid lavas, that is, more often in the highly siliceous ones. After solidification the contraction is unequal in the different layers, producing cracks that split the mass in plates parallel to the planes of flow. This tabular or platy parting may be accompanied by a more or less pronounced prismatic cracking, generally in large prisms.

The thickness of the plates may be one-sixteenth of an inch or several inches, the thinner cracking being called platy and the thicker tabular. The plates are not generally of any considerable lateral extent, being several inches to several feet in diameter. This is probably the commoner kind of platy parting in rhyolites, phonolites, trachytes, and andesites. It is well developed in the lithoidal rhyolite at Obsidian Cliff, and is shown in Fig. 19. It may be developed to some extent in the finer-grained intrusive rocks.

A subsidiary parting is sometimes developed across the plates that are parallel to the planes of flow. They are close together and normal to the surface of the plates, and occur at right angles to the direction of greatest stress within the plate, such as may be produced by the stretching of the sheet when resting on a hillside.

Jointing and cracking produced by shearing and pressure should be distinguished from those just described. They are commonly accompanied by slipping and faulting, with slicken-sides, and in extreme cases with layers of

FIG. 19. PLATY PARTING IN LITHOIDAL RHYOLITE, OBSIDIAN CLIFF.

crushed rock. These may occur in quite irregular positions, and the fractured rocks may be shattered into fragments of various sizes embedded in a matrix of comminuted particles. This usually happens in the neighborhood of a profound fault. Such a mass becomes a crushed breccia.

Shearing cracks may be almost parallel, giving rise to slaty and schistose cleavage. Or they may divide the mass into large slabs, or flat blocks, as in the case of some granites and gneisses. Jointing in several directions causes the rock to break into more or less regularly shaped polyhedrons, or into irregularly shaped fragments or sherds.

**Structures of aggregation** in tuffs and breccias indicate their mode of accumulation. They may be bedded or unbedded. When bedded the distinctness of the layers depends mainly on the fineness of the material. Tuff composed of fine particles may have sharply defined layers, which may differ in the coarseness of the fragments, some approaching layers of sand, or conglomerates, in appearance, but the individual grains being angular to subangular. When the fragments vary in size in each layer, and reach several inches to a foot in diameter, the bedding is less sharply marked, the surface planes of successive layers not being even in most cases. Often the bedding is quite pronounced when seen at a distance, but is much less so upon close inspection. Generally the larger fragments are more abundant in the lower part of each layer. The thickness of a layer may be anything, from several inches to several feet.

The rock fragments are angular to subangular, and the proportion between small and large fragments varies between wide extremes. In some instances rounded stones occur with angular ones, and a large part of the material may be rounded and waterworn, when the bedding and arrangement of the material are like those in sedimentary gravels and conglomerates, showing assortment and sometimes false bedding.

Unbedded tuff and breccia form great masses without sign of arrangement. Fragments of all sizes are mingled without order. Such accumulations may be a few feet thick or hundreds of feet, constituting the major part of mountain masses. The weathering of these unbedded accumulations often produces characteristic forms. Massive tuffs are sometimes cut down by surface waters into tower-like forms with conical summits. The erosion of massive breccias frequently produces pinnacled towers and buttresses with rough and irregular surfaces, due

to the projection of angular blocks of compact lava from the more easily eroded matrix, called hoodoos in Western America. These may cover a large area on a mountain slope, as at Hoodoo Mountain, in the Absaroka Range, Wyoming.[1]

**Eutaxitic Structure.** — When exploded fragments of molten magma, large or small, fall together in a still heated condition,

FIG. 20. WELDED PUMICE, YELLOWSTONE NATIONAL PARK.

as may readily happen within the crater of a volcano or in the mouth of a fissure, they may be plastic enough to weld together into a more or less compact, coherent mass. This may subsequently flow like other lava, and is known as FLOW-BRECCIA. The result of such fragmentation and welding is shown in the brecciated appearance of the rock, which, if a volcanic glass, may consist of angular pieces different in color, in the size and distribution of the crystals, in texture, and in denseness. In some instances these pieces may be drawn out into streaks, as the lava flowed; and this may proceed to such an extent that the former brecciated character is obscured, and lamination is produced. This streaked and blotched appearance of a lava is called EUTAXITIC STRUCTURE.

[1] Monograph 32, U. S. Geological Survey, 1899, Pt. 2, p. 223.

FIG. 21. PARTIALLY COLLAPSED PUMICE, YELLOWSTONE NATIONAL PARK.

FIG. 22. WELDED PUMICE WITH AXIOLITES, YELLOWSTONE NATIONAL PARK.

The same operation may result in the welding of exploded pumice, or of collapsed pumice that was highly inflated. The distinction between this and a flow breccia is chiefly in the size of the welded fragments. When the magma furnishing the particles is strongly colored, it sometimes happens that the color disappears at the surface of the fragments, or is changed to another tint, so that when they are welded together their former shape is shown by the light-colored outline of parts of the rock when seen in thin section, as in Fig. 20, from dense welded rhyolitic pumice. In case the collapse has not been complete, there may be many porous spaces, and if the lava has flowed enough to draw out the welded glass, the structure appears as in Fig. 21. In a completely welded pumice that has been long drawn out, the structure is that shown in Fig. 22. In this rock spherulitic crystallization has arranged itself along the axes of the welded threads, producing a texture known as axiolitic, already described in connection with spherulitic crystallization. These examples of welded pumice are from rhyolitic lavas in the Yellowstone National Park.[1]

[1] Monograph 32, U. S. Geological Survey, 1899, p. 404.

# PART II

## *NOMENCLATURE AND CLASSIFICATION OF IGNEOUS ROCKS*

## CHAPTER I

### HISTORICAL SKETCH

**Introduction.** — Having become acquainted with the characteristics of igneous rocks so far as concerns their chemical and mineral composition, their mode of crystallization and texture, and the manner in which they may become differentiated and erupted from deep-seated reservoirs, the questions naturally arise as to how they occur in various regions, in what association with one another, and what are the special characteristics of the many different kinds of igneous rocks that have been produced on the earth. Answers to these questions must be in the nature of descriptions of specific rocks, their occurrence at particular centers of eruption, and their association in petrographical provinces. But in order to do this it is necessary to employ terms, or names, for various kinds of rocks so as to simplify descriptions and to make use of the store of information supplied by innumerable descriptions and statements to be found in the literature of the subject. These two purposes cannot be accomplished, however, in the same manner, for the names and terms used in the literature of petrography have been given on such different bases and have been employed in such diverse ways often, that their use does not always simplify the description or discussion of igneous rocks, but rather confuses them. In order that names of rocks should be of greatest service they should be capable of as precise definition as possible, and their application should be invariable. For these reasons they should be given to systematically arranged varieties of rocks, which may be placed in groups of different orders of magnitude, or of comprehensiveness. In a new and rapidly growing science, how-

ever, this is not possible. Names must be employed for rocks before their precise character and their relation to other rocks are known, and when these are learned, the definitions of names in use must become modified. Commonly they become more restricted in their application; new names are needed and are introduced. Thus the nomenclature in a particular subject grows; often without system; commonly from suggestions of individual petrographers. Names, so given, survive if found by other writers to be useful and appropriate; if not, they remain unused and are generally harmless. There has grown up in this way a vocabulary of rock names which have very different degrees of exactness, and in some cases a considerable range of usage or application, so that it is necessary to know the period in which they were used, and the particular petrographer who employed them. Recently an entirely new nomenclature has been suggested for igneous rocks, which is coming into general use, so that the student must become acquainted with two different nomenclatures,—an old one, which is acknowledged to be seriously defective and inadequate, and a new one that is not completely developed.

Names have been suggested or employed from time to time for particular kinds or varieties of igneous rocks with little or no regard to any classification of the rocks, and so may be used for these rocks no matter how they may be classified. Names given to groups, or classes, of rocks are generally peculiar to certain systems of classification, and are part of the terminology of a system. A proper understanding of the nomenclatures and terminologies, as well as the classifications of igneous rocks, in present use by petrographers in various parts of the world, must rest on a knowledge of the history of the growth of petrology in the past century, a complete account of which has not been written. An important contribution to the subject, however, may be found in a "Review of the Development of Systematic Petrography in the Nineteenth Century," by Cross.[1] Some idea of the changes that have taken place in the nomenclature and classification of igneous rocks may be gotten from the following very brief sketch of the usages with regard to some of the principal rock names,

[1] Cross, W. C. Jour. Geol., vol. 10, 1902, pp. 431–499; also Quantitative Classification of Igneous Rocks, Chicago, 1902, pp. 1–94.

and of essential features of different classifications, the latter derived largely from the review by Cross.

**Growth of Nomenclature.** — A few of the commonest names of igneous rocks in present use have come down from the times of Theophrastus and of Pliny, and may be found in Greek and Roman writings. These are, *syenite, porphyry, basalt, basanite, obsidian,* while other names were originally used by workers in stone, chiefly in Italy, and were afterwards adopted by geologists. Such are, *granite* and *gabbro.*

SYENITE was originally applied to the rock at Syene (Assuan) in Upper Egypt, largely used by the ancients for making monuments and obelisks (Pliny). This rock contains much quartz, and is now called a hornblende-granite. The name syenite was applied by Werner in 1787 to rocks of the Plauen Grund, near Dresden, composed chiefly of feldspar and hornblende, without quartz. The use of the name syenite became diverse from now on. Haüy in 1822, and Leonhard in 1823, apply it to feldspar-hornblende rocks without quartz. Brongniart in 1813 used it for rocks with these minerals together with quartz, and this usage has persisted among many geologists to within recent times.

It is to be noted that differences in the character of the feldspars in rocks were not recognized or used in their definition until about 1836, by von Buch. In 1841 syenite was defined as an orthoclase-hornblende rock. In 1849 the term was extended by Rose to rocks with orthoclase and biotite; and in 1875 vom Rath made it include rocks with orthoclase and augite. In 1887 Rosenbusch extended the term to include rocks composed chiefly of alkali-feldspar and any ferromagnesian mineral; hornblende, mica, or pyroxene.

BASALT has had a somewhat different experience. The origin of the term is uncertain, and may have been derived from Ethiopian, *bselt* or *bsalt,* cooked or baked (Pliny). It was first applied to dense, dark volcanic rocks or lava; was used in this sense by Werner; was thought to consist chiefly of amphibole (Haüy), but was found by Cordier to be preponderantly pyroxene, with other minerals. A synonymous term of ancient origin was *basanite.* Leonhard, in 1823, considered basalt as very fine-grained dolerite, and composed of pyroxene, feldspar, and magnetite. He recognized transitions from basalt to dolerite, phonolite and trachyte. It was not until 1870 that the microscopical studies by Zirkel demonstrated that rocks called basalt varied greatly in composition, and were then given various names. The name basalt is still used in a restricted sense by some petrographers, and as a comprehensive term by others.

PORPHYRY is a name given by the ancients to a rock on account of its purple color, πορφυρίτης (*porphyrites lapis*). The rock was dense, lithoidal, and spotted with light-colored crystals of feldspar. The name became significant of the spotted appearance, and not the color, and was applied to spotted rocks of various colors. As early as 1813, Brongniart began to make new words by using the syllable -phyre as a suffix; thus *melaphyre*

was given to black porphyry. In 1826 von Buch used the word *rhombenporphyre;* and later it entered such compounds as *augitophyre* (1852), *orthophyre, leucitophyre,* etc. (Coquand, 1857).

OBSIDIAN has been used in only one sense, apparently, from ancient times, — for black volcanic glass.

GRANITE was used as early as 1596 by Cæsalpinus, and appears to have been applied to any granular rock. Wallerius appropriated it for a rock composed of feldspar, quartz, and mica, and Werner used it in this sense in 1787. Leonhard (1823) recognized the presence of several kinds of micas and accessory minerals, such as hornblende, tourmaline, and numerous others. Its relation to aplite (Retz) and pegmatite (Haüy), and its gradation into syenite and diorite, were known at this time. As in the case of syenite, the character of the feldspar was subsequently fixed as orthoclase, and in 1887 made to embrace all alkali-feldspars, by Rosenbusch. Likewise the definition was extended to all quartz-alkali-feldspar rocks containing mica, hornblende, or pyroxene. It is used at present in various senses; in some cases in a narrow sense; in others, in almost the original, vague manner.

PHONOLITE (Klaproth, 1801), formerly called *klingstein* by Werner (1787), was defined by Haüy (1822) as compact feldspar with uneven conchoidal fracture and greenish gray color, and as grading through a great number of modifications into basalt. Its chemical behavior toward acids was early noted, 1805; sanidine was recognized as a constituent in 1828 by Gmelin, and the presence of nephelite was determined by Rose in 1839. A microscopical study by Zirkel in 1867 showed its true mineral composition.

TRACHYTE was applied by Haüy, before 1813, to rocks, composed of feldspar, whitish to ash-gray, having a rough appearance; often porphyritic with glassy feldspars, which are sometimes striated. These rocks include those formerly called trap-porphyry by Werner (1787) and domite by von Buch. Some had been called granite-porphyry by Nose, 1789. The trachytes of the Siebengebirge were formerly called granite. Their volcanic origin had been demonstrated by Humboldt (Geogn. Versuch, 1823). Trachytes were of widespread occurrence in Europe and in the South American Cordillera. When differences in feldspars became known, the many kinds of rocks called trachyte began to be distinguished by names. In 1836 those supposed to contain chiefly andesine were called *andesite* by von Buch; and those characterized by orthoclase (sanidine) were considered by some petrographers as trachytes, while others urged the retention of the name for all the rocks to which it was first applied; from this has resulted great confusion in the use of the name, trachyte. *Andesite* has been applied to rocks of this kind containing all varieties of feldspar more calcic than oligoclase, except those called basalt, and so has become a much more general term than trachyte, which at present has a limited application.

These examples of usage at different times and by various petrographers will serve to show the manner in which the present petrographical nomenclature has come into existence.

It grew out of the attempts of early geologists and mineralogists to describe the rocks as they found them in the earth, or in museum collections.

**Growth of Classifications.** — The early efforts of Linnæus to classify objects in the mineral kingdom met with little success, owing to ignorance as to their actual character. In the last part of the eighteenth century more definite knowledge of minerals made a clearer understanding of rocks possible. Explorers and geologists were unraveling the intricate relationships of rock masses, and making clear the stratigraphic sequence of sedimentary formations. The early classifications of rocks by Haidinger and Werner were in large part concerned with the supposed order of their succession or superposition, and the descriptive portions were hampered by lack of precise knowledge of the constituents of the rocks. So far as possible at that time the definitions were often clear expressions of the megascopic appearance of particular rocks.

The following names of igneous rocks were among those employed by Werner: *syenit, granit, schriftgranit, porphyr, grünstein, graustein, klingstein, perlstein, pechstein, mandelstein, trapp, basalt, lava.*

With the beginning of the nineteenth century interest in the composition and character of rocks increased rapidly through the mineralogical achievements of Haüy in Paris. He proposed to classify rocks on a mineral basis, and in 1822 published a classification in which rocks of very different origin were grouped together according to mineral resemblances. Prior to this, in 1813, Brongniart had published a somewhat similar classification, which was reissued in much better form in 1827. The investigations of Cordier during these years into the chemical and mineral composition of volcanic rocks (published in 1815) were instrumental in advancing the subject materially.

Among the rock names employed by Brongniart in 1813 are: *diabase* (grünstein, Werner); *variolite*, an old term; *basanite* (basalt), both old terms; *melaphyre* (trapp-porphyr, Werner); *amygdaloide* (mandelstein, Werner); *domite*, previously used by von Buch; also several names already used by Haüy; *pegmatite, trachyte.* In 1822 Haüy used, besides the names just mentioned, *diorite* (d'Aubuisson, 1819) (grünstein, Werner). This rock had many modifications, from phanerocrystalline to "basaltic" and "amygdaloidal" varieties; *aphanite* (d'Aubuisson, 1819) (trap, porphyry of the

ancients, variolite); *dolérite* ("groundmass of feldspar surrounding crystals of pyroxene;" "resembling fine-grained diorite;" "variety of graustein of Werner"); *phonolite* (Klaproth) (klingstein, Werner); *basalt* ("originally thought to consist in large part of amphibole, but shown by Cordier to be largely pyroxene") contains much iron; also the French forms of the old words, obsidian, perlite, pitchstone, pumice. The term *gabbro* was introduced by von Buch in 1810, and *minette* was used by de Beaumont in 1822.

In London, as early as 1822, Macculloch undertook the classification of rocks chiefly on a geological basis; that is, by formations. At the same time (1823) in Heidelberg appeared the first considerable publication of great value as distinctly a treatise on rocks. It was "Charakteristik der Felsarten," by Karl Cæsar von Leonhard. In this he combined clear ideas of the relationship between geological occurrence and petrographical characters of rocks. However, the system of classification is not based on definitely stated principles. The chief groups are: (1) Heterogeneous rocks, (2) Homogeneous rocks, (3) Fragmental rocks, (4) Loose rocks. Further divisions were made in some cases upon textural characters, as granular, schistose, porphyritic, dense and glassy. It is interesting to note that Leonhard introduced almost no new names for igneous rocks. He is credited with having first used the terms *felsit* and *anamesit*.

In France, Brongniart (1827) issued a classification of rocks in which he distinguished plainly between minerals, rocks, and geological terranes, or formations. He pointed out the difference between a consideration of the composition and characters of rocks and that of their geological occurrence, and held that a classification of rocks must be based on their characteristics, composition and texture. His system comprises two principal divisions: (1) Homogeneous, or simple, rocks; (2) Heterogeneous, or composite, rocks. Their identification is based on megascopic characters. Homogeneous rocks are divided into (1) Those composed of recognizable minerals (roches phanérogènes), and (2) those having an unrecognizable constitution (roches adélogènes). Heterogeneous rocks are divided into (1) "roches de cristallisation," and (2) "roches d'agrégation," which introduces the idea of origin, or mode of formation, but this was not commented on by Brongniart at the time.

The studies of such a keen observer as De la Beche in England

led to the general recognition of systematic classification of rocks as distinct from other treatments of their relationships, and in 1833 he divided rocks into *stratified* and *unstratified;* the stratified being subdivided into *superior* or *fossiliferous*, and *inferior* or *non-fossiliferous*. These divisions correspond to sedimentary, metamorphic, and igneous.

The investigations into the chemical composition of rocks and of their mineral constituents by Cordier, Abich, Bunsen, von Waltershausen, Bischof, Scheerer, Roth, Streng, Delesse, Houghton, and others took place about this period. One of the notable results of these studies, especially those of Rose and Abich, was the emphasis put upon the character of the feldspars in rocks, which has become a prominent factor in modern mineralogical classifications of igneous rocks. It led to the introduction by von Buch, in 1835, of the term *andesite*, primarily for rocks of the Andes, containing andesine feldspar. Another result showed itself in the grouping of volcanic rocks in *basic*, *intermediate*, and *acid* divisions by Abich in 1841; or in *acid*, *hybrid*, and *basic* groups by Durocher in 1857; or in *acid*, *neutral*, *basic*, and *ultra basic* divisions by Kjerulf in 1857. These conceptions were also connected with theories as to the origin of volcanic, or igneous, rocks.

In 1850 there appeared an important contribution to the subject of rock classification by Naumann, at Leipzig. Its chief significance lies in the method of treatment, since its author was a great systematist, and of the many ways in which he discussed the relationships of rocks, one section was called "Petrographie oder Gesteinslehre." This is probably the first use of the term *petrography*, and was used in the broad, general sense now attached to petrology. He recognized six divisions in his treatment of petrography: (1) a discussion of the constituents of rocks, (2) the texture and structure of rocks, (3) the forms of their occurrence, (4) the systematic description of rocks, (5) the genesis of rocks, (6) their alteration. But it appears that his system of classification for purposes of description, beyond the first division into *original* and *derived*, was without logical sequence. The chief value of his work rests in the clear presentation of the scope of the science of rocks.

In 1855 Von Cotta, of Freiberg, published his "Gesteinslehre," in which he maintained that the more fundamental characters of rocks were their chemical and mineral composition, that the

latter should be made the basis for the definition of the names of rocks, and that texture should be employed for their further qualification. In a second edition, in 1862, rocks are grouped primarily according to their mode of formation as, *eruptive, metamorphic,* and *sedimentary.*

About this time there appeared a work by Coquand (Paris, 1858) which resembles that of Naumann in certain respects. It recognizes three families of rocks: *igneous, aqueous, metamorphic.* Igneous rocks are divided into (1) granitic, in the sense of granular; (2) porphyritic; (3) volcanic. Coquand used for the first time the names, *pyroxenite,* and *orthophyre, oligophyre, leucitophyre.*

An attempt at a chemical classification of rocks was made by Senft in 1857, but it was highly artificial and unsystematic, and left little or no impression upon the development of petrography. Quite otherwise was the result of the studies by Roth, who collected and published from time to time analyses of rocks made by various analysts. The first collection of analyses was published in 1861, and was accompanied by a discussion of the chemical and mineral composition of igneous rocks. He recognized the fact that chemically similar rocks may have different mineral compositions, that a purely chemical classification is not feasible, and that a mineralogical classification must be connected with the texture. He classified rocks on a mineral basis, primarily with respect to the feldspars, and the presence or absence of quartz, as follows:

I. *Orthoclase rocks* (often containing some oligoclase).
   A. *With quartz* (i.e., more siliceous than orthoclase).
      1. Granite.
      2. Gneiss.
      3. Felsite-porphyry.
      4. Liparite.
      5. Syenite.
   B. *Without quartz.*
      1. Orthoclase-porphyry.
      2. Sanidine-trachyte.
      3. Sanidine-oligoclase-trachyte.
      4. Phonolite.
      5. Leucitophyre.

II. *Oligoclase rocks.*
   A. *With hornblende.*
      1. Diorite.
      2. Porphyrite.
      3. Amphibole-andesite.
   B. *With augite.*
      1. Oligoclase-augite-porphyry.
      2. Melaphyre and spilite.
      3. Pyroxene-andesite.
      4. Nephelinite.
      5. Haüynophyre.

III. *Labradorite rocks.*
   1. Labradorite-porphyry.
   2. Gabbro.
   3. Hypersthenite.
   4. Diabase.
   5. Dolerite.
   6. Normal pyroxenic rock (Bunsen).
   7. Basalt.

IV. *Anorthite rocks.*
   A. With augite, eukrite.
   B. With hornblende.

In this work Roth used the term *liparite* for what had been called *quartz-trachyte* by some petrographers. The previous year, 1860, von Richthofen named the same kind of rocks *rhyolite*, and also employed *lithoidite* for the lithoidal varieties. The terms *eleolite-syenite* and *foyaite* were used by Blum in 1861. In 1863 Sterry-Hunt, in Canada, introduced the term *anorthosite*, for rocks almost wholly composed of lime-soda-feldspar. In 1864 de Lapparent applied the name *monzonite* to the syenitic rocks of Monzoni, and Hochstetter gave the name *dunite* to the olivine-rock of New Zealand. In 1866 *pikrite* was first used by Tschermak, and *ditroite* by Zirkel.

A work of far-reaching influence appeared in 1866, Zirkel's *Lehrbuch der Petrographie*. It was a treatise of great richness of information, in which the method of treatment reflected many of the ideas expressed in the more important systems of classification just noted. The classification adopted was as follows:

*A*. Original crystalline rocks.
- I. Simple rocks.
- II. Composite rocks.
  1. Composite crystalline-granular and porphyritic rocks.
  2. Composite crystalline-schistose rocks.

*B*. Clastic rocks.

Igneous rocks (II, 1) were divided into *older* and *younger* rocks, although the artificial character of such a distinction was recognized. A mineralogical division similar to that employed by Roth was used, with the distinction of *feldspathic* and *non-feldspathic* rocks, and those containing the feldspathoids, nephelite and leucite.

In 1868 was published von Richthofen's monograph, "Principles of the Natural System of Volcanic Rocks." In it he proposed to use genetic relationship, or origin, as the fundamental basis of classification, grouping together all volcanic rocks. The next factor was texture, producing the divisions, granitic, porphyritic, and volcanic; these he considered as geologically separate. Mineral composition was regarded as essentially dependent on chemical composition, and as more convenient for definition of rocks. The resulting classification was:

Class I. Granitic Rocks.
Orders: (1) Granite; (2) Syenite; (3) Diorite; (4) Diabase.

Class II. Porphyritic Rocks.
Orders: (1) Felsitic porphyry; (2) Porphyrite; (3) Melaphyre; (4) Augitic porphyry.

Class III. Volcanic Rocks.
Orders: (1) Rhyolite; (2) Trachyte; (3) Propylite; (4) Andesite; (5) Basalt.

Further mineralogical distinctions were expressed by Families under Orders.

Although the microscope was employed as early as 1774,[1] and more especially in the first decades of the nineteenth century by Cordier,[2] in the study of rock fragments and powders, its real application to the investigation of rocks was not made until 1850, when H. Clifton Sorby,[3] in Sheffield, England, prepared thin sections of calcareous grit and studied its structure. Such section had been made of fossil woods by Nicol and Witham[4] in 1831, but Sorby was the first to apply the method to the study of rocks. The new method of petrographical research found its most ardent followers in Germany, where rapid advances were made in the elucidation of the problems of the aphanitic rocks, more especially those of igneous origin. Among the first and more important contributors to microscopical petrography were Zirkel, Rosenbusch, Fischer, Vogelsang, von Lasaulx, vom Rath, Stelzner, Streng, and Möhl in Germany; Sorby and Allport in England; Fouqué and Michel-Lévy in France; Tschermak, Doelter, and Bořicky in Austro-Hungary; Törnebohm in Sweden. Many other petrographers contributed in lesser degree to the advancement of the new science. In the United States the earliest writers of about this period, before 1880, were Hawes, Pumpelly, and Wadsworth. The number of students of petrography increased rapidly, and their works will be reviewed or noted in the descriptive part of this book, Volume II. The many names of rocks proposed within this period of twenty-five years have become so much a part of the present system of qualitative mineralogical classification, about to be described in detail, that no attempt will be made to sketch the history of their introduction. A brief statement, however, of the development that has taken place in the classification of igneous rocks since the beginning of microscopical petrography is necessary.

The first comprehensive treatise that was published in this period was *Die Mikroskopische Beschaffenheit der Mineralien und Gesteine*, by F. Zirkel, in 1873, which deals chiefly with "massive

[1] "D. F." Rozier's Obs. s. la phys. IV, 1774, p. 255.

[2] Cordier, P. L. A. Journal des Mines, XV, No. 227, p. 259, and Ann. d Chim. et Phys. III, 1816, p. 285.

[3] Sorby, H. C. Quar. Jour. Geol. Soc., London, 1851, vol. vii, p. 1.

[4] Witham, H. Edinburgh and London, 1831, 48 pp., 6 Pl.; also Neues. Jahrb. f. Min., etc., 1833, p. 456.

composite" rocks, that is, igneous rocks. They are arranged in the following divisions:

I. Orthoclase Rocks.

(1) With quartz; (2) Without quartz, with or without plagioclase; (3) Without quartz, with nephelite (or leucite).

II. Plagioclase Rocks.

With (1) hornblende; (2) augite; (3) diallage; (4) hypersthene; (5) mica; (6) olivine.

III. Nephelite Rocks.

IV. Leucite Rocks.

Subdivisions based on particular kinds of lime-soda-feldspars employed in his former treatise on petrography were set aside, since the microscope showed them in error. Under each division of rocks the phanerocrystalline forms were first described, and then the older porphyritic varieties, followed by the corresponding volcanic lavas and glasses.

In 1873 also appeared the first volume of Rosenbusch's *Mikroskopische Physiographie der Mineralien und Gesteine;* namely, that dealing with the rock-making minerals. The second volume treating of igneous rocks was published in 1877. In it the system of classification was:

*A*. Rocks with orthoclase feldspar.
*B*. Rocks with orthoclase and nephelite (or leucite).
*C*. Rocks with plagioclase.
*D*. Rocks with plagioclase and nephelite (or leucite).
*E*. Rocks with nephelite.
*F*. Rocks with leucite.
*G*. Rocks without feldspar, or feldspathic constituents; that is, olivine-rocks.

Rocks belonging to *A* were subdivided according to age, then according to the presence or absence of quartz, and then according to texture; thus:

*A*. Orthoclase Rocks.
(*a*) Older.

I. With quartz.
(1) Granular. Family of granites.
(2) Porphyritic. Family of quartz-porphyries.
(3) Glassy. Family of felsite-pitchstones.

II. Without quartz.
(1) Granular. Family of syenites.
(2) Porphyritic. Family of quartzless porphyries.
(3) Glassy. Apparently wanting.

(*b*) Younger.

I. With quartz.

(1) and (2) Granular or porphyritic. Family of liparites.

(3) Glassy. Family of acid glasses. Obsidian, trachytic pitchstone, perlite, pumice.

II. Without quartz.

(1) and (2) Granular and porphyritic. Family of trachytes.

(3) Glassy. To this belong a part of (*b*) I (3).

The same method of subdivision was applied to the remaining principal divisions.

In 1879 the first microscopical treatise on minerals and rocks in France was published by Fouqué and Michel-Lévy: *Minéralogie micrographique.* It contains a brief statement of their system of classifying igneous rocks, which is based on: (1) the mode of formation; (2) the geological age; (3) the specific mineral properties; nature of the minerals; and the texture of the rock. These latter criteria are applied in a partial and arbitrary manner. The system, while still employed in France, has not influenced rock classification in other countries. On the other hand, optical methods for the microscopical investigation of minerals have been highly elaborated by the French, and have come into general use.

The works of Rosenbusch and Zirkel have become text-books for American and English students of petrography and have exerted great influence upon the course of development of the science. In England, however, the principle of an age distinction among igneous rocks was early combated, especially by Allport; it being generally held that igneous rocks of similar compositions are alike when solidified under similar conditions regardless of the age at which they may have been erupted. The same position was early taken by petrographers in America, having been advocated by J. D. Dana long before this time. The petrographical classification adopted by Dana, however, was a mineralogical one, which did not accord with those of modern petrographers. The effect of microscopical study was to emphasize the importance of mineralogical and textural characters of rocks to the neglect of other equally important characteristics. The first reaction was voiced chiefly by Lossen, who urged the significance of the geological relations of igneous rocks, their occurrence, and mode of formation. The second edition of Rosenbusch's *Mikroskopische Physiographie,* in

1887, shows the influence of Lossen's ideas, for in it igneous rocks are divided into three groups: (1) Deep-seated rocks; (2) Dike rocks; (3) Effusive rocks. This is intended to express a relationship between the mode of occurrence and texture. But the relationship is so imperfect that the terms selected to designate these divisions invited immediate criticism, and the method of treatment actually followed in the work was according to texture and not strictly according to geological occurrence as indicated by the terms used. The principal idea attached to the group of so-called dike rocks was that they are products of differentiation from deep-seated bodies of magma, a conception applicable to nearly all varieties of igneous rocks, including effusive rocks. The first two divisions were not subdivided according to difference of age, but effusive rocks were so divided, into paleovolcanic and neovolcanic rocks. The mineralogical divisions were essentially the same as in the first edition, except that alkali-feldspars appear in place of orthoclase. A third edition, in 1896, further emphasizes Rosenbusch's views on magmatic differentiation, but does not present any fundamental changes in the system of classification. In this work no use is made of the specific chemical composition of the rocks. But in a smaller treatise of a more general character, *Die Elemente der Gesteinslehre*, published in 1898, chemical analyses of rocks are given a prominent place.

A second edition of Zirkel's *Lehrbuch der Petrographie*, in 1893–94, consists of three volumes, one on general principles and the characteristics of rock minerals, one on igneous rocks, and one on metamorphic and sedimentary rocks. Igneous rocks are classified by: (1) mineral composition; (2) texture; (3) age. The mineralogical divisions are essentially the same as those in the first edition, except that alkali-feldspars replace orthoclase. And it is to be noted that an age distinction is applied only to porphyritic, aphanitic and glassy rocks. The chemical composition of rocks is recognized by the introduction of chemical analyses of a limited number of rocks of various kinds.

The foregoing may be considered as an introduction to what may be called the Qualitative Mineralogical System of Classification of igneous rocks, the two best expositions of which are to be found in the text-books of Rosenbusch and Zirkel.

# CHAPTER II

## QUALITATIVE MINERALOGICAL SYSTEM OF CLASSIFICATION OF IGNEOUS ROCKS

It is proposed in the following statement to give the definitions of various kinds of igneous rocks essentially as they may be found in the works of Rosenbusch and of Zirkel, without attempting to present either system of classification distinctly as such. That is, the definitions will be given in terms of their mineral composition and texture, without any expression of views as to the possible genetic relations of the rocks to one another. Such definitions are very nearly the same in both works cited, but the arrangement is different in the two cases. In Rosenbusch's system texture is placed before composition; in Zirkel's, composition is the basis of classification. For specific information as to the details of each method the student is referred to the writings of these petrologists cited in the previous chapter. Comment and criticism of the Qualitative System will be found as an introduction to the statement of the Quantitative System in the succeeding chapter.

Confusion in the statement of any complex system involving numerous variable factors arises from the difficulty of presenting it properly either verbally, which is necessarily a linear expression, or by a tabular or diagrammatic arrangement, which is commonly one with two coördinate axes of reference. The number of mineral components and the textural variations are so many that no single table can express in detail any classification of igneous rocks.

The mineralogical-textural definitions about to be given are arranged in groups on a basis of mineral composition expressed in terms of the principal components, and are subdivided to a slight extent on a further distinction of texture. The method of arrangement will appear from the accompanying table, in which the distinctions between different divisions are in some instances more specific than those in general use;

| | | | I. Rocks Chiefly Quartz. | II. Rocks Characterized by Quartz and Feldspar. | III. Rocks Characterized by Feldspar. |
|---|---|---|---|---|---|
| A. Alkalic Feldspars. | 1. Little ferromagnesian minerals. | a | **Quartz veins, quartz-pegmatites (in part).** | **Granites, aplite, pegmatite, alsbachite, alaskite, quartz-lindoite, ekerite, rockallite, charnokite, rapakiwi, granite-porphyry.** | **Syenites, aplite, pegmatite, lestiwarite, lindoite, hedrumite, nordmarkite, pulaskite, umptekite, laurvikite, albitite, tönsbergite, akerite (in part).** |
| | | b | ... | α. Rhyolites, liparite, tordrillite, pantellerite, quartz-pantellerite, comendite, dacite (in part), nevadite, etc.<br>β. *Quartz-porphyry, grorudite, quartz-tinguaite, paisanite, ailsyte, quartz-keratophyre, quartz-porphyrite dacite-porphyry in part, felsite (in part), granophyre, etc.* | α. Trachytes, domite ...<br>β. *Orthophyre, keratophyre (in part), sölvsbergite, bostonite, mænaite, rhombenporphyry (in part), felsite (in part).* |
| | 2. Much ferromagnesian minerals. | a | ... | ... | **Shonkinite (in part), malignite (in part).** |
| | | b | ... | ... | α. Mica-trachyte ...<br>β. *Syenitic lamprophyres, minette, vogesite.* |
| B. Calci-Alkalic Feldspars. | 1. Little ferromagnesian minerals. | a | ... | **Quartz-monzonite, granodiorite, quartz-diorite (in part), tonalite, adamellite, banatite (in part).** | **Monzonite, augite-syenite (in part), akerite (in part), diorite (in part), ornoite, gabbro (in part), essexite (in part), malchite (in part), luciite.** |
| | | b | ... | α. Dellenite, dacite (in part), volcanite,<br>β. *Dellenite-porphyry, dacite-porphyry, quartz-porphyrite.* | α. Latite, vulsinite, ciminite, trachy-andesite, trachydolerite, banakite, shoshonite, monhaldeite, andesite, aleutite, verite, sanukite, mijakite, basalt (in part).<br>β. *Gauteite, andesite-porphyry, porphyrite, weiselbergite, propylite.* |
| | 2. Much f-m. m. | a | ... | ... | **Kentallenite, olivine-monzonite, durbachite, vaugnerite.** |
| | | b | ... | ... | α. Absarokite ...<br>β. *Kersantite, spessartite, camptonite (in part).* |
| C. Soda-Calcic Feldspars. | 1. Little ferromagnesian minerals. | a | ... | **Quartz-diorite (in part).** | **Anorthosite, kyschtymite, kedabekite, gabbro, hyperite, norite, troctolite, eucrite, essexite (in part), beerbachite, dolerite, diabase (in part).** |
| | | b | ... | α. Dacite (in part) | α. Basalt (in part), tachylyte.<br>β. *Melaphyre, diabase (in part), proterobase, ophite, variolite.* |
| | 2. Much f-m. m. | a | ... | ... | **Gabbro (in part), allivalite, harrisite.** |
| | | b | ... | ... | α. Basalt (in part) ...<br>β. *Diabase (in part), odinite* |
| (AB) C. | 3. Chiefly ferromagnesian minerals. | a | ... | ... | **Peridotites, wehrlite, eulysite, harzburgite, saxonite, lherzolite, picrite, cortlandtite, scyelite, kimberlite, dunite, pyroxenite, diallagite, etc., websterite, ariégite, hornblendite, magnetite-olivenite, titaniferous magnetite rock.** |
| | | b | ... | ... | α. Limburgite, augitite ...<br>β. *Picrite-porphyry (in part)* |

| | | | IV. Rocks Characterized by Feldspar and Feldspathoids. | V. Rocks Characterized by Feldspathoids. |
|---|---|---|---|---|
| A. Alkalic Feldspars. | 1. Little ferromagnesian minerals. | a | **Nephelite-(eleolite)-syenite, litchfieldite, mariupolite, ditroite, miascite, sodalite-syenite, cancrinite-syenite, foyaite, laurdalite, lujaurite, pseudo-leucite-syenite, borolanite.** | **Urtite, sussexite, sodalite-rock, tawite.** |
| | | b | α. Phonolite, apachite, leucite-phonolite, leucitophyre.<br>β. *Tinguaite, leucite-tinguaite, nephelite-rhombenporphyry.* | ........................................ |
| | 2. Much ferromagnesian minerals. | a | **Nephelite-malignite, shonkinite (in part).** | **Ijolite, nephelinite (in part), missourite, jacupirangite.** |
| | | b | α. Orendite, wyomingite .......<br>β. *Camptonite* (*in part*), *monchiquite* (*in part*). | α. Nephelinite (in part), haüynophyre, noseanite, nephelite-basalt, leucitite, leucite-basalt, madupite, melilite-basalt, venanzite, euktolite.<br>β. *Monchiquite, fourchite, ouachitite, alnöite.* |
| B. Calci-Alkalic Feldspars. | 1. Little ferromagnesian minerals. | a | **Theralite, essexite (in part)** .... | ........................................ |
| | | b | α. Tephrite, leucite-tephrite, kulaite. | ........................................ |
| | 2. Much f-m. m. | a | **Theralite (in part)** ........................ | ........................................ |
| | | b | α. ........................................<br>β. *Farrisite* | ........................................ |
| C. Soda-Calcic Feldspars. | 1. Little ferromagnesian minerals. | a | **Teschenite** ........................ | ........................................ |
| | | b | α. Basanite, leucite-basanite .... | ........................................ |
| | 2. Much f-m. m. | a | ........................................ | ........................................ |
| | | b | α. Basanites (in part) .......... | ........................................ |
| (AB) C. | 3. Chiefly ferromagnesian minerals. | a | ........................................ | ........................................ |
| | | b | ........................................ | ........................................ |

from which it follows that the names of some varieties of rock occur in more than one division in the table. This is chiefly due to the distinctions recognized among the lime-soda-feldspars, those preponderantly sodic being separated from those preponderantly calcic. The divisions expressed in the table are as follows: Five major divisions in vertical columns, based on the dominance of I, quartz; II, quartz and feldspar; III, feldspar; IV, feldspar and feldspathoid, nephelite, leucite, sodalite; V, feldspathoid. Then divisions, in horizontal lines, based on the general character of the preponderant feldspathic constituents: A, alkalic; B, calci-alkalic, that is, preponderantly alkalic; C, soda-calcic, preponderantly calcic; D, without feldspars or feldspathoids. Further divisions, in horizontal lines, of each of these divisions are based (1) on the small amount of ferromagnesian minerals present in the rock; (2) on the abundance of ferromagnesian minerals. A distinction with respect to texture separates the (*a*) phanerocrystalline rocks from (*b*) aphanitic ones, the latter being divided into ($\alpha$) those with cenotypal habit, and ($\beta$) those with paleotypal habit.

Further divisions on a basis of the kinds of ferromagnesian mineral or other minerals, or of specific textures, will appear in the description of each group of rocks.

## I. ROCKS CHIEFLY QUARTZ

With very subordinate amounts of feldspar and little or no ferromagnesian minerals.

### A1. Quartz-Pegmatite

(*a*) **Phanerocrystalline Texture.** QUARTZ VEINS AND QUARTZ-PEGMATITES, in part. — Rocks of this kind belong almost wholly to I, A. 1. The feldspar is alkalic, orthoclase or albite; muscovite may be present, and very small amounts of rare minerals. The texture is phanerocrystalline, evenly granular to inequigranular, and sometimes porphyritic to graphic in varieties with more feldspar. With increasing amounts of feldspar there is a transition into granite-pegmatite, of which intrusive quartz-veins are extreme mineral facies or differentiations. No aphanitic or porphyry-like equivalents of these rocks are known.

## II. CHARACTERIZED BY QUARTZ AND FELDSPAR

Oftener with preponderant feldspars, which are in most cases, A, chiefly alkalic, furnishing the granite–rhyolite group of rocks; less often, B, chiefly calci-alkalic feldspars, characterizing the granodiorite (quartz-monzonite) –dellenite group; rarely, C, chiefly soda-calcic feldspars, yielding quartz-diorite–dacite rocks, in part. In each of these groups the ferromagnesian constituents are subordinate in amount.

### A I. Granite and Rhyolite.

Chiefly quartz and alkali-feldspars, which may be orthoclase, microcline, albite, microperthite, soda-microcline (anorthoclase). With these may be associated, in subordinate amounts, oligoclase, andesine; rarely more sodic varieties of labradorite; also mica, amphibole and pyroxene, with still smaller amounts of numerous other minerals, especially in the phanerocrystalline forms of these rocks. Rocks of this group are in some instances strongly potassic, when the feldspar is chiefly orthoclase or microcline; or they may be strongly sodic, having albite or soda-microcline as the preponderant feldspars; others may be intermediate between these extremes, with nearly equal amounts of orthoclase and albite, or with microperthite or soda-orthoclase as the chief feldspars. The highly sodic varieties usually contain sodic amphiboles or sodic pyroxenes instead of common hornblende, or diopside, augite, or orthorhombic pyroxenes.

(*a*) **Phanerocrystalline Texture,** sometimes porphyritic. — GRANITE. — ALKALI-GRANITES when there are few calcium-bearing minerals; CALCI-ALKALIC-GRANITES when these minerals are relatively abundant. According to the kinds of feldspathic minerals that preponderate, and the nature of the characteristic subordinate minerals, there have been recognized the following varieties of granite.

***Alkali-granites***

Chiefly quartz and alkali-feldspars, with little or no lime-soda-feldspar.

APLITE[1] (granitic). — With almost no muscovite or other subordinate mineral.

ALSBACHITE.[2] — Porphyritic granitic aplite with phenocrysts of quartz and orthoclase. Sometimes with garnet.

[1] Retz. [2] Chelius, 1892.

QUARTZ-LINDOITE.[1] — A lindoite (p. 362) with notable amount of quartz; closely related to syenitic aplite.

ALASKITE.[2] — Quartz and alkali-feldspars, without mica or other constituents.

GRANITE PEGMATITE. — With muscovite, and frequently with rare minerals, and sometimes corundum.

MUSCOVITE-GRANITE (in part). — With muscovite.

RIEBECKITE-GRANITE. — With riebeckite as the characteristic subordinate mineral.

EKERITE.[3] — With arfvedsonite or ægirite and a little biotite.

ROCKALLITE.[4] — Quartz, albite, ægirite-acmite, in nearly equal proportions.

*Calci-alkalic-granites*

Chiefly quartz and alkali-feldspars with considerable lime-soda-feldspars and subordinate amounts of other minerals.

MUSCOVITE-GRANITE (in part). — Characterized by muscovite.

MUSCOVITE-BIOTITE-GRANITE. — Called "granite proper" by Rosenbusch, or granite in the narrower sense.

BIOTITE-GRANITE OR GRANITITE.[5] — Without muscovite.

HORNBLENDE-BIOTITE-GRANITE. — Hornblende-granitite, RAPAKIWI of Finland.

HORNBLENDE-GRANITE. — Without biotite.

PYROXENE-GRANITE. — With little or no hornblende or biotite. The pyroxene may be diopside; possibly augite in some instances; also enstatite or hypersthene in others. CHARNOKITE[6] is hypersthene-granite.

Numerous transitions exist between varieties of granite containing biotite, hornblende, and pyroxene. Other minerals occurring in small amounts in these rocks are titanite, apatite, magnetite, hematite, ilmenite, zircon, garnet, tourmaline, and others less frequently.

The *texture* is holocrystalline and phanerocrystalline; the fabric is chiefly granular; equigranular in some instances; inequigranular and seriate in others; hiatal and porphyritic in still others. Coarse-grained granites with porphyritic fabric are commonly called PORPHYRITIC GRANITE. When they are medium to fine-grained they are called GRANITE-PORPHYRY. But this name

[1] Brögger, 1894. [2] Spurr, 1900. [3] Brögger, 1906.
[4] Judd, 1897. [5] Rose, 1857. [6] Holland, 1900

is sometimes applied to aphanitic porphyries having the same composition as the phanerocrystalline ones. Graphic fabric is common, especially in pegmatite, GRAPHIC GRANITE, in which quartz and alkali-feldspars are intergrown. Miarolitic texture, characterized by numerous minute cavities, is sometimes present. Streaked or banded texture is occasionally developed pyrogenetically, sometimes as *schlieren*, sometimes through shearing and metamorphism. Orbicular texture occurs rarely.

*Transitions* of granite into other kinds of rocks take place with increase or decrease in certain mineral constituents. Thus with decrease in quartz there is a gradation to syenite; with decrease of feldspars a gradation to quartz veins; with increase of lime-soda-feldspar there is a transition to granodiorite; with increase of lime-soda-feldspar and decrease in quartz a transition to monzonite, diorite, and gabbro. These are accompanied by corresponding changes in the ferromagnesian minerals.

(*b*) **Aphanitic Texture,** often porphyritic. RHYOLITE (liparite) and QUARTZ-PORPHYRY and the corresponding glassy rocks.— The composition is recognized when the rocks are porphyritic by the presence of phenocrysts of quartz and alkali-feldspars, rarely those of lime-soda-feldspar, with very few of ferromagnesian minerals, oftenest biotite, in a groundmass, which is composed of microscopic crystals of quartz and alkali-feldspars, or is glass having the chemical composition of a mixture of these minerals. The groundmass is therefore lithoidal in some cases, and then generally light colored; or glassy in others, and often dark colored to black, sometimes gray to white.

Aphanitic rocks have received in many instances two sets of names for mineralogically and chemically equivalent varieties, one set being applied in most cases to older rocks that have undergone some alteration so that the feldspars have become dull and lusterless. In other cases, however, the more crystalline and more compact aphanitic rocks have been given the same names as the older ones. Rocks with the appearance or *habit* of older ones have a *paleotypal* habit; those resembling recent lavas have a *cenotypal* habit, according to Brögger.[1] In this group of rocks the first have been called QUARTZ-PORPHYRIES,

[1] Brögger, W. C. Die Eruptivgesteine des Kristianiagebietes, I, p. 87, Christiania, 1894.

the latter RHYOLITE (liparite). Varieties have been distinguished in some cases on a basis of their composition, in others on that of their texture. Owing to the common custom of laying more stress on the character of the phenocrysts than on that of the groundmass in many porphyritic aphanitic rocks the correlation of aphanitic and phanerocrystalline rocks is not always in accord with their actual composition, since one group is classified and defined in terms of all its mineral components, while the other is treated in terms of only a part of them, and sometimes the quantitatively subordinate part. Thus it happens that porphyritic aphanitic rocks composed of quartz, and alkali-feldspars with subordinate amount of lime-soda-feldspar, which correspond to some calci-alkalic-granites, are not grouped with the aphanitic forms of the quartz-alkali-feldspar rocks, because the lime-soda-feldspars often appear relatively more abundant as phenocrysts than the alkali-feldspars, which are chiefly in the groundmass. They are commonly grouped with phanerocrystalline rocks of II, B, 1 — granodiorites. They properly belong with the granites. The following names have been given to aphanitic, or glassy, quartz-alkali-feldspathic rocks:

*a Cenotypal Habit*

RHYOLITE.[1] — A general name for rocks of this division, chiefly quartz and alkali-feldspars, with little or no lime-soda-feldspar and very small amounts of mica (biotite), pyroxene, or hornblende; having various degrees of crystallinity, from holocrystalline to perhyaline, and possessing various kinds of fabric. When porphyritic, the phenocrysts are commonly quartz and sanidine, or soda-orthoclase, less often albite, besides fewer micas, pyroxenes, or hornblendes.

LIPARITE.[2] — A synonym of rhyolite. These rocks were at one time called *quartz-trachyte.*

TORDRILLITE.[3] — Rhyolite composed almost wholly of quartz and alkali-feldspars, without ferromagnesian components.

PANTELLERITE.[4] — Chiefly quartz, soda-microcline (anorthoclase), ægirite-augite, together with diopside and cossyrite. Porphyritic, with a lithoidal to glassy groundmass. Quartz is

[1] von Richthofen, 1860. [2] Roth, 1861. [3] Spurr, 1900. [4] Förstner, 1881.

not abundant as phenocrysts. When in notable amount the rock has been called QUARTZ-PANTELLERITE.

COMENDITE.[1] — Chiefly quartz, alkali-feldspar, with ægirite, arfvedsonite or riebeckite, biotite, and brown hornblende. Porphyritic, with lithoidal groundmass.

DACITE[2] (in part). — Chiefly quartz, alkali-feldspars and subordinate lime-soda-feldspar, with mica, pyroxene, and hornblende. Porphyritic, with lithoidal or glassy groundmass.

The following terms, based on texture, have been applied to rhyolites in whole or in part:

LITHOIDITE.[3] — A rhyolite having a lithoidal or "stony" groundmass; that is, aphanitic and dull, not vitreous; porphyritic or not.

HYALORHYOLITE. — One having a glassy groundmass; porphyritic or not.

NEVADITE.[4] — A rhyolite in which the phenocrysts are so abundant that they equal or exceed in amount the groundmass. Sempatic to dosemic.

PERLITE (rhyolitic). — With glassy groundmass having perlitic structure. Porphyritic or not.

OBSIDIAN (rhyolitic). — With dense glassy groundmass having conchoidal fracture. It may or may not be porphyritic.

PUMICE (rhyolitic). — With highly vesicular, pumiceous structure. Porphyritic or not.

### *β Paleotypal Habit*

QUARTZ-PORPHYRY. — The equivalent of rhyolite or liparite, usually denser.

GRORUDITE[5] — QUARTZ-TINGUAITE. — Chiefly quartz, alkali-feldspar, with ægirite. Porphyritic, with dense, lithoidal groundmass; phenocrysts: feldspar, ægirite, and rarely quartz. Analogous to pantellerite.

PAISANITE[6] — AILSYTE.[7] — Chiefly quartz, soda-orthoclase, with some arfvedsonite-riebeckite. Porphyritic, with few, small phenocrysts of feldspar and quartz; groundmass dense, compact to very fine-grained phanerocrystalline; analogous to comendite.

[1] Bertolio, 1895. [2] von Hauer and Stache, 1863. [3] von Richthofen, 1860. [4] *Idem.*, 1868. [5] Brögger, 1894. [6] Osann, 1893. [7] Heddle, 1897.

QUARTZ-KERATOPHYRE. — Chiefly quartz, albite, sometimes with microperthite, soda-microcline, or oligoclase-albite, and a little biotite. Porphyritic, with dense lithoidal groundmass, rarely very fine-grained phanerocrystalline.

KERATOPHYRE[1] (in part). — Some rocks without phenocrysts of quartz that have been called keratophyre belong here because of the quartz in the groundmass.

QUARTZ-BOSTONITE (in part). — Chiefly alkali-feldspars with quartz and almost no other minerals. Dense, lithoidal, in some instances slightly porphyritic and then called quartz-bostonite-porphyry. These rocks are sometimes phanerocrystalline and fine grained.

QUARTZ-PORPHYRITE — DACITE-PORPHYRY — in part. — The more alkalic porphyries, composed chiefly of quartz and alkali-feldspar, with some lime-soda-feldspar; paleotypal equivalents of the more alkalic dacites.

The following terms based on texture have been applied to paleotypal rocks of this division in whole or in part:

FELSITE[2] (in part). — Non-porphyritic lithoidal rock, chiefly quartz and alkali-feldspar.

FELSITE-PORPHYRY. — The same rock when porphyritic.

FELSOPHYRE.[3] — The same when the groundmass is micro-cryptocrystalline or microfelsitic.

GRANOPHYRE.[3] — Quartz-porphyry with lithoidal groundmass that is microgranular. This has been called *microgranite* by Rosenbusch, and the term granophyre has been used by him for a porphyry of this kind with micrographic fabric.

VITROPHYRE[3] (in part). — Quartz-porphyry with glassy groundmass.

PITCHSTONE (in part). — Glassy rock of this composition having paleotypal habit, that is, a dull or resinous luster; porphyritic or not.

The *texture* of these rocks when studied microscopically is highly varied both as to crystallinity, from holocrystalline to glassy, and as to granularity, from almost phanerocrystalline to microcryptocrystalline. The fabric may be equigranular, inequigranular, seriate or hyatal; often porphyritic. It may be micrographic, less often micropoikilitic. Spherulitic or radial

[1] Gümbel, 1874. [2] Gerhard. [3] Vogelsang, 1867.

fabric is common. Glasses are microlitic, often with pronounced flow-texture or lamination, and frequently exhibit eutaxitic or pyroclastic texture, or that of welded breccia or collapsed pumice.

*Transitions* of aphanitic rocks of this group into those of closely related groups are common. With decrease in quartz they grade into trachyte, tinguaite, and keratophyre. With increase in lime-soda-feldspar they pass into dellenite, toscanite, and dacite. With decrease in quartz and increase in lime-soda-feldspar they grade into latite, vulsinite, ciminite, and andesite, and into corresponding paleotypal forms. There are no rocks of group II, A, which contain much ferromagnesian minerals and would form a division, II, A, 2.

## B 1. GRANODIORITE AND DELLENITE, QUARTZ-DIORITE AND DACITE

Characterized by quartz and calci-alkalic feldspar, with subordinate amounts of biotite, hornblende, and pyroxene, with still smaller amounts of the iron oxides, titanite, garnet, apatite, and other minerals. The expression calci-alkalic feldspars may be made to mean potash-feldspars and soda-calcic feldspars, or feldspars that are intermediate between alkali-feldspars and soda-calcic feldspars. Thus it may be applied to combinations of potash-feldspar (orthoclase, microcline) with soda-lime feldspars, andesine-labradorite or labradorite in nearly equal proportions, or it may apply to lime-soda-feldspars having the composition of andesine ($Ab_3An_1 - Ab_1An_1$). This is introducing a distinction not always employed in the definition of igneous rocks, since it recognizes a notably potassic group as contrasted with a strongly sodic group.

(*a*) **Phanerocrystalline Texture,** sometimes porphyritic. QUARTZ-MONZONITE, GRANODIORITE, QUARTZ-DIORITE (in part). — According to the kinds of feldspars and ferromagnesian minerals the following varieties have been distinguished:

QUARTZ-MONZONITE.—Chiefly quartz, lime-soda-feldspar (andesine, labradorite) with considerable potash-feldspar (orthoclase); with these may be biotite, hornblende, or pyroxene. Often classed as granite.

GRANODIORITE.[1] — Nearly the same as quartz-mozonite, but with somewhat less potash-feldspar, intermediate in composition between quartz-monzonite and quartz-diorite.

QUARTZ-DIORITE (in part). — Chiefly quartz and lime-soda-feldspars, having an average composition of andesine. With these may be associated a small amount of orthoclase and one or more ferromagnesian minerals, giving the following varieties:

QUARTZ-MICA-DIORITE. — With biotite as the chief ferromagnesian mineral.

QUARTZ-MICA-HORNBLENDE-DIORITE. — TONALITE is a variety with andesine as the preponderant feldspar.

QUARTZ-HORNBLENDE-DIORITE. — Commonly called QUARTZ-DIORITE.

QUARTZ-MICA-HYPERSTHENE-DIORITE and QUARTZ-AUGITE-DIORITE; usually accompanied by hornblende. ANDENDIORITE and BANATITE (in part) belong in this variety of quartz-diorites.

ADAMELLITE.[2] — A quartz-diorite of variable composition. In part it may be considered a variety of tonalite, with muscovite and biotite. In part it grades into facies with orthorhombic pyroxene, yielding hypersthene-granite and norite. According to Brögger adamellite is equivalent to quartz-monzonite.

Transitions exist between the varieties mentioned. They contain slightly more ferromagnesian minerals than rocks of division II, A, but always subordinate amounts. There are no rocks of division II, B, with preponderant ferromagnesian minerals. Varieties low in these minerals constitute pegmatitic or aplitic modifications of these rocks, corresponding to pegmatites and aplites of granite.

The *textures* are very similar to those in granites; non-porphyritic and porphyritic forms occur. When the porphyritic rocks are medium to fine grained they are called QUARTZ-DIORITE-PORPHYRY.[3] Special characteristics of the fabrics of some of these rocks will be described in Volume II.

*Transitions* to granite occur with increase of alkali-feldspars.

[1] Becker and Lindgren, 1891. [2] Cathrein, 1890.

[3] When the characteristic feldspars are lime-soda-feldspars it is customary with many petrographers to use the term *porphyrite* instead of *porphyry*, but this seems inadvisable, and will not be followed in this book.

When quartz decreases there is gradation to monzonite and diorite, and when this is accompanied by increase in the calcic character of the feldspars and in the amount of pyroxene the rocks pass into gabbro.

(*b*) **Aphanitic Texture,** often porphyritic. DELLENITE and DACITE (in part) and DACITE-PORPHYRY (quartz-porphyrite) (in part) and the corresponding glassy rocks. — When porphyritic the phenocrysts are chiefly lime-soda-feldspar, quartz, and sometimes potash-feldspar, with one or more of the minerals biotite, hornblende, and pyroxene. The groundmass consists chiefly of feldspars, which are commonly more alkalic than the lime-soda-feldspar phenocrysts, and with more potash-feldspar than appears as phenocrysts, besides quartz and some ferromagnesian minerals, with magnetite, apatite, etc. Or the groundmass may be more or less glassy when the chemical composition of the whole rock corresponds to that of holocrystalline varieties. For the reasons already stated in connection with the porphyritic aphanitic rocks of division II, A 1, (*b*) the presence of notable amounts of potash-feldspar may not be shown by the phenocrysts, since it may remain in the groundmass. This is true also of the quartz, there being relatively more quartz present in the rock in most cases than is indicated by the amount of quartz phenocrysts. The varieties are:

*α. Cenotypal Habit*

DELLENITE.[1] — Chiefly quartz and lime-soda-feldspar, with notable amounts of potash-feldspar and subordinate ferromagnesian minerals. The aphanitic or glassy equivalent of quartz-monzonite. When porphyritic, the phenocrysts of lime-soda-feldspar are often accompanied by those of potash-feldspar, sanidine, besides quartz, and ferromagnesian minerals. They are what might have been called quartz-trachy-andesites.

DACITE (in part). — Chiefly quartz and lime-soda-feldspar, with little or no potash-feldspar, subordinate amounts of biotite, hornblende, or pyroxene, yielding the following varieties:

BIOTITE-DACITE, BIOTITE-HORNBLENDE-DACITE, BIOTITE-HORNBLENDE-PYROXENE-DACITE, corresponding varieties without biotite and so on. These rocks are sometimes called QUARTZ-

[1] Brögger, 1895.

ANDESITES. It is to be noted that there are no varieties with sodic amphiboles or sodic pyroxenes.

VOLCANITE.[1] — A glassy rock from Vulcano, Lipari Islands, with few phenocrysts of soda-microcline and andesine, augite and sometimes olivine. Its chemical composition is that of dacite.

QUARTZ-BASALT (in part). — Chiefly andesine feldspar, pyroxene, olivine, quartz, iron oxides, which may be phenocrysts in a groundmass of feldspar, pyroxene, iron oxide, and glass. Textural varieties analogous to those in the preceding division are:

HYALODACITE, dacitic perlite, obsidian and pumice.

*β. Paleotypal Habit*

DELLENITE-PORPHYRY and DACITE-PORPHYRY, commonly called quartz-porphyrite. — There are the same varieties characterized by different ferromagnesian minerals as are noted under dacite.

There are no rocks of this group so rich in ferromagnesian minerals as to constitute a second division, II, B 2.

The *texture* of these rocks is highly varied, though not quite so much so as that of rocks of II, A 1, (*b*). The fabrics are similar except for increase of lime-soda-feldspars and consequent changes in fabric. Spherulitic fabric occurs less frequently than in the more alkalic quartzose rocks.

*Transitions* of these rocks with decrease in quartz are to latite (trachyandesite) and to andesite; with increase in potash-feldspars they grade into rhyolite. Corresponding transitions occur in the paleotypal forms.

## C 1. QUARTZ-DIORITE AND DACITE (IN PART)

Characterized by quartz and soda-calcic feldspar, labradorite, with subordinate amounts of potash-feldspar and ferromagnesian minerals. There are few rocks belonging to this group for the reason that the more calcic the rock the less siliceous it is as a general rule, so that there are few rocks whose feldspars are strongly calcic that contain much quartz, and

[1] Hobbs, 1894.

some aphanitic rocks, that are chemically equivalent to phanerocrystalline rocks of this group, do not exhibit quartz, and are generally classed with non-quartzose rocks.

(*a*) **Phanerocrystalline Texture.** QUARTZ-DIORITE (in part). — Some rocks with labradorite feldspar and considerable quartz, and subordinate hornblende, pyroxene, and mica, have been called quartz-diorite, though they might have been classed as quartz-hornblende-gabbros with equal propriety, according to some definitions of gabbro. Ordinary quartz-gabbros contain too small an amount of quartz to be placed in this group. The rocks of this group may contain biotite, and do not differ from most quartz-diorites except in the more calcic character of the feldspar, which averages labradorite instead of andesine.

(*b*) **Aphanitic Texture.** DACITE (in part). — Rocks having the composition described have in some cases been named dacite when quartz is present as phenocrysts. But when it is confined to the groundmass as microscopic anhedrons scarcely distinguishable from the feldspar owing to similar optical behavior, or is still in the uncrystallized magma as glass, the rocks are called andesites, and are classed with the non-quartzose group. They are then only recognized by the chemical composition of the rock as a whole.

## III. ROCKS CHARACTERIZED BY FELDSPAR

Sometimes without quartz or feldspathoids, but commonly with variable small amounts of one or the other. In order to distinguish rocks of this division having a little quartz from those of the preceding one with considerable quartz it would be advantageous to qualify the name of the rock by the term *quartz-bearing* instead of simply prefixing *quartz-*, since in some cases this method has been employed to form the name of the corresponding quartzose rock belonging to the more quartzose division II, as quartz-diorite. But there is no uniformity of practice in this regard. The same observations apply to the matter of leucite, nephelite and the sodalites. There is the widest range of variety in the feldspars of this division, and a wide range in the proportions of ferromagnesian minerals, which may sink to almost nothing, or may preponderate over

feldspars of various kinds, reaching the highest proportion in connection with the more calcic feldspars. Three subdivisions may be recognized according as the feldspars are chiefly alkalic, calci-alkalic, or soda-calcic; and those with more alkalic feldspars may be further distinguished according as potassic or sodic feldspars preponderate.

### A 1. SYENITE AND TRACHYTE

Chiefly alkali-feldspars, with subordinate amounts of muscovite or one or more of the ferromagnesian minerals, and sometimes small amounts of lime-soda-feldspars, quartz, or feldspathoids. The alkali-feldspars may be orthoclase, microcline, sanidine, soda-orthoclase, soda-microcline (anorthoclase), or albite. There may be some oligoclase or andesine. The ferromagnesian minerals may be biotite, lepidomelane, hornblende, or sodic amphiboles, diopside, augite, or sodic pyroxene; also olivine in certain cases. Titanite, apatite, iron oxides, and other minerals in small amounts are often present. Leucite, nephelite, and sodalite occur in some instances. Transitions from quartz-bearing varieties to those bearing feldspathoids frequently occur.

(*a*) **Phanerocrystalline Texture,** sometimes porphyritic. — SYENITE is a common group name, which may be qualified by mineral names as prefixes according to the characteristic subordinate components. But special names have been given to particular varieties. Distinctions similar to those recognized in the granite group have been based on the abundance of alkali-feldspars or the presence of some oligoclase or andesine with potash-feldspar.

***Alkali-Syenites***

APLITE (syenitic). — Alkali-feldspars with small amounts of ægirite, arfvedsonite, or riebeckite.

LESTIWARITE.[1] — Quartz-bearing aplite of alkali-syenite.

SYENITIC PEGMATITE. — With muscovite, and often with rare minerals, sometimes corundum.

LINDOITE[2] (bostonite, in part). — Quartz-bearing aplitic syenite, chiefly albite and orthoclase intergrown as micro-

[1] Rosenbusch, 1896. [2] Brögger, 1884.

perthite, with subparallel, tabular crystals forming a fine-grained, somewhat laminated rock.

HEDRUMITE.[1] — Nephelite-bearing lindoite with a little sodalite, ægirite, and lepidomelane.

NORDMARKITE.[1] — Chiefly microperthite, soda-orthoclase, and albite, with a little biotite, ægirite, and sometimes quartz. The texture is granular, medium to coarse grained.

PULASKITE.[2] — Chiefly orthoclase (cryptoperthite), with a little nephelite or sodalite and variable, small amounts of biotite, diopside, and (?) barkevikite. The feldspars are tabular and their arrangement is diverse.

UMPTEKITE.[3] — Chiefly microperthite, with small, variable amounts of nephelite, sodic amphibole which may be arfvedsonite, riebeckite, or barkevikite; sometimes pyroxene.

LAURVIKITE.[1] — Chiefly microperthite and soda-microcline (anorthoclase), having a rhomboid tabular form, approaching that of the phenocrysts in rhombenporphyry, with variable, subordinate amounts of titaniferous augite, diopside, ægirite-augite, sometimes hypersthene, lepidomelane, and barkevikitic amphibole, sometimes olivine, nephelite, and sodalite, less often a little quartz.

SODALITE-SYENITE. — Chiefly orthoclase, albite, microperthite, or soda-microcline, with small amounts of sodalite, and barkevikite, or biotite and diopside; having a granular texture.

ALBITITE.[4] — Chiefly albite, with very little else, having a fine-grained granular texture.

ÆGIRITE-SYENITE. — Chiefly alkali-feldspars with ægirite as the characteristic subordinate mineral. There are alkali-syenites characterized similarly by arfvedsonite or riebeckite.

### *Calci-Alkalic Syenites*

MICA-SYENITE. — Chiefly orthoclase and oligoclase, with subordinate biotite and some hornblende, quartz, titanite, etc.; granular texture.

HORNBLENDE-SYENITE. — Chiefly orthoclase, with oligoclase and subordinate hornblende, and some biotite, pyroxene, quartz, and titanite; granular texture.

[1] Brögger, 1890. [2] J. F. Williams, 1890. [3] Ramsay, 1894. [4] Turner, 1896.

TÖNSBERGITE.[1] — Chiefly orthoclase and andesine, with the fabric of lauvikite; sometimes a little quartz and other minerals.

AKERITE[2] (in part). — Chiefly orthoclase and oligoclase, or andesine, with biotite, diopside, or ægirite-augite, and quartz; texture fine-grained granular, or with tabular fabric.

RHOMBENPORPHYRY (in part). — Some varieties are phanerocrystalline; for definition see the aphanitic division.

QUARTZ-SYENITE. — A general term which may be used for any quartz-bearing syenite.

Transitions from one variety of syenite to another are common, especially between those varieties most closely related chemically and mineralogically. The minerals occurring in small amounts in most of these rocks are: zircon, which is a prominent constituent in some instances; apatite, magnetite, hematite, ilmenite, or titanite; and less frequently, in the pegmatites, the rarer minerals tourmaline, garnet, corundum, etc.

The *texture* is holocrystalline and phanerocrystalline, with various fabrics; in some varieties the fabric is granular, in others more or less tabular, with subparallel or diverse arrangement, chiefly in the alkali-syenites. The rocks may be equigranular, inequigranular, seriate, or hiatal and porphyritic. Coarse-grained porphyritic rocks of this group are called PORPHYRITIC SYENITES; the medium- to fine-grained porphyritic forms are SYENITE-PORPHYRIES. But this term is also applied to aphanitic porphyries of this group. Fine-grained porphyritic forms of any of the varieties of syenite noted above may be designated by terms compounded of the varietal name with porphyry, thus: pulaskite-porphyry, nordmarkite-porphyry, etc.

*Transitions* of syenite to granite occur with increase of quartz, and are common. With increase in nephelite there is gradation to nephelite-syenite. With increase in calcic feldspars syenites pass into monzonites, diorites, or gabbros. With increase in ferromagnesian minerals, chiefly pyroxene and olivine, there is a transition to shonkinite.

(*b*) **Aphanitic Texture,** often porphyritic. TRACHYTE and corresponding porphyries, QUARTZLESS PORPHYRY, ORTHOPHYRE, etc., and the glassy equivalents. — These rocks when porphyritic usually have phenocrysts of alkali-feldspar, in some instances

[1] Brögger, 1899. [2] *Idem.*, 1890.

calci-alkalic feldspar, besides mica, amphibole, or pyroxene, but none of quartz. The groundmass consists chiefly of alkali-feldspars, with or without subordinate amounts of the minerals just mentioned. The glasses are recognized by microlites of the minerals named, but most definitely by the chemical compositions corresponding to those of syenites. The lithoidal varieties are usually light-colored, generally with duller luster than that of the more quartzose lithoidal forms of the granite group. Glassy varieties may be various shades of color to black.

*α. Cenotypal Habit*

TRACHYTE.[1] — A general name for rocks of this division with aphanitic or glassy texture, composed chiefly of alkali-feldspars, with little or no calci-alkalic feldspar, and one or more of the following minerals: mica, pyroxene, amphibole, olivine, nephelite, leucite, sodalites, or quartz, etc.; having various degrees of crystallinity from holocrystalline to holohyaline, and various fabrics. Often characterized by fibrous to thin-tabular fabric, produced by thin prismoids or plates of alkali-feldspar; sometimes called "trachytic" fabric. When prismatic the characteristic phenocrysts are alkali-feldspars. Some of the varieties of trachyte are:

***Alkali-Trachytes.*** — Chiefly rich in sodium, and therefore in sodic minerals. Almost no calci-alkalic feldspar; chiefly soda-orthoclase, soda-microcline (anorthoclase), or albite, with sodic pyroxene, ægirite, ægirite-augite, and sodic amphiboles arfvedsonite, riebeckite, katophorite, as distinctive. In some instances there are small amounts of nephelite, sodalites, or leucite, and a close relationship to phonolites. Mineralogical varieties may be called ÆGIRITE-TRACHYTE, RIEBECKITE-TRACHYTE, etc.

***Calci-Alkalic Trachytes***

MICA-TRACHYTE, AUGITE-TRACHYTE, SANIDINE-OLIGOCLASE-TRACHYTE, which may contain variable, small amounts of oligoclase or andesine and sometimes a little quartz, belong to the more calcic division of trachytes. With them is to be grouped DOMITE,[2] which is chiefly oligoclase and sanidine, with small

[1] Haüy, 1811. [2] von Buch.

amounts of hornblende or pyroxene; porous and rather friable to compact, with glistening luster and light grayish color; scarcely porphyritic.

The following terms, based on texture, have been applied to trachytes, as to other glassy lavas:

HYALOTRACHYTE. — A trachyte with glassy groundmass.

PERLITE (trachytic). — Having a glassy groundmass with perlitic structure.

OBSIDIAN (trachytic). — Dense glass with conchoidal fracture.

PUMICE (trachytic). — Highly vesicular or pumiceous.

*β. Paleotypal Habit*

*Alkalic Division*

ORTHOPHYRE,[1] OR QUARTZLESS PORPHYRY. — General terms applied to dense porphyries of this group with phenocrysts of orthoclase and none of quartz, having a paleotypal habit.

KERATOPHYRE[2] (in part). — Porphyries of this group rich in sodium; feldspar phenocrysts chiefly soda-microcline (anorthoclase). The rocks originally called keratophyre are somewhat altered, and the ferromagnesian minerals are generally decomposed. Some of these rocks contain so much quartz as to belong to division II, A 1, (*b*), *β*.

SÖLVSBERGITE.[3] — Chiefly alkali-feldspar, mostly albite and microcline, with ægirite, sometimes with katophorite or arfvedsonite, and mica; in some instances there is a little quartz, in others a little nephelite; grading into grorudite on the one hand and into tinguaite on the other. The texture is aphanitic to fine-grained, with tabular-feldspars, often in subparallel arrangement, producing a schistose texture. Only slightly porphyritic.

BOSTONITE.[4] — Chiefly alkali-feldspar, microcline, microperthite, soda-microcline, seldom orthoclase. Other minerals almost absent, or in very small amounts. Aphanitic, light-colored rocks, sometimes slightly porphyritic, often non-porphyritic. The feldspars are tabular, sometimes subparallel, producing a satin luster on cleavage planes in the somewhat fissile varieties.

*Calci-Alkalic Division*

MÆNAITE.[5] — Calcic bostonite, also called OLIGOCLASE-PORPHYRY, like bostonite with considerable oligoclase.

[1] Coquand, 1857. [2] Gümbel, 1874. [3] Brögger, 1894.
[4] Rosenbusch, 1882. [5] Brögger, 1898.

RHOMBENPORPHYRY[1] (in part). — Chiefly alkali-feldspar, with potash-oligoclase in phenocrysts having characteristic wedge-shaped tabular forms that yield narrow rhombic sections. The dense lithoidal groundmass consists of alkali-feldspar, with small amounts of augite and ægirite-augite, biotite, olivine, apatite, titaniferous magnetite, zircon. In some instances there is nephelite. These porphyries range from aphanitic to fine-grained phanerocrystalline forms, which should be called syenite-porphyries.

FELSITE (in part). — Some felsites are almost wholly alkali-feldspars, like bostonite.

The *textures* of aphanitic rocks of this group when seen with the microscope vary in crystallinity from holocrystalline to highly glassy, and range through all gradations of micro-granularity. The fabric is sometimes granular, but oftener formed by thin tabular crystals, which may be subparallel or diverse in arrangement — a *trachytic* fabric. Thin tabular crystals are frequent as microlites in the glasses, but fiber-like prismoids are also characteristic of some varieties of microtexture.

*Transitions* from trachytes into rhyolites are common through increase of quartz, and into phonolite through increase in nephelite. With increase in calcic feldspars there is passage into latite, vulsinite, ciminite or trachyandesite, trachydolerite, and into andesite and basalt. Corresponding transitions occur between paleotypal forms.

### A 2. SHONKINITE AND SYENITIC LAMPROPHYRES

Composed of alkali-feldspar, mostly orthoclase, with albite or oligoclase in some instances, and abundant ferromagnesian minerals, augite, hornblende, mica, olivine. Rocks of this group are not common, and are oftener porphyry-like than evenly granular.

(*a*) **Phanerocrystalline Texture.** — Only a few rocks belonging to this division have been described. They are facies of syenitic rocks rich in ferromagnesian constituents.

SHONKINITE[2] (in part). — Medium-grained, evenly granular rocks, composed of augite, with biotite and olivine, and subordinate amounts of orthoclase, with small amounts of albite

[1] von Buch. [2] Pirsson, 1895.

and soda-microcline and a little nephelite and sodalite. Shonkinite is a marginal facies of sodalite-syenite, II, A 1, (*a*), at Square Butte, Montana. A somewhat similar rock from Ahvenvaara, Finland, contains pyroxene, potash-soda-feldspar, and 14 per cent of apatite.

GARNET-PYROXENE-MALIGNITE.[1] — Chiefly microperthite as phenocrysts in a fine-grained groundmass of ægirite-augite, melanite, biotite, titanite, apatite, with some feldspar.

AMPHIBOLE-MALIGNITE.[1] — Chiefly microperthite, arfvedsonitic amphibole, with ægirite-augite, biotite, titanite, and apatite. Texture granular, slightly porphyritic. The malignites are not quite so rich in ferromagnesian minerals as shonkinite. They are closely related to nephelite rocks.

(*b*) **Porphyritic fine-grained** to *aphanitic* rocks whose phenocrysts are almost wholly ferromagnesian minerals have been called LAMPROPHYRES. A part of them belong in this group, and are known by the general term SYENITIC LAMPROPHYRES. More specifically they are:

*α. Cenotypal Habit.* — Certain mica-trachytes with abundant phenocrysts of biotite.

*β. Paleotypal Habit*

MINETTE[2] (mica-trap).—Dark-colored, porphyritic rock, aphanitic to fine-grained, seldom medium-grained phanerocrystalline. The phenocrysts are chiefly biotite, with or without augite or hornblende, sometimes with olivine. The groundmass consists of these minerals with orthoclase, sometimes with soda-microcline or oligoclase. Apatite is rather abundant. Varieties with mica alone, without hornblende or augite, are rare. HORNBLENDE-MINETTE contains hornblende in addition to mica; AUGITE-MINETTE contains augite and mica. With increase in alkalic feldspars these lamprophyres grade into syenitic porphyry.

VOGESITE.[3] — Syenitic lamprophyre without mica. The phenocrysts are hornblende, diopside, or augite; sometimes a little olivine may be present. The feldspar is chiefly orthoclase, with variable amounts of lime-soda-feldspar; apatite is also noticeable. There may be HORNBLENDE-VOGESITE and AUGITE-VOGESITE. These rocks are associated with granite, and are rarer than minettes.

[1] Lawson, 1896. [2] de Beaumont, 1822. [3] Rosenbusch, 1887.

**B I. MONZONITE AND LATITE, DIORITE AND ANDESITE**

Chiefly calci-alkalic feldspars, with subordinate amounts of biotite, hornblende, or pyroxene. There may be also a little quartz or feldspathoids, nephelite, sodalites, or leucite, besides titanite, apatite, iron oxides, and zircon. As in group II, B 1, calci-alkalic feldspar may signify alkali-feldspars and soda-calcic feldspars, or feldspars intermediate between alkali-feldspars and soda-calcic feldspar. That is, the feldspars may be potash-feldspar, orthoclase, with labradorite or andesine-labradorite, or they may be andesine.

(*a*) **Phanerocrystalline Texture,** sometimes porphyritic. MONZONITE and DIORITE (in part). — Two divisions of these rocks may be recognized according as there is a notable amount of potash-feldspar present or not.

***Potassic Division***

MONZONITE.[1] — Chiefly andesine or labradorite, with considerable orthoclase and biotite, hornblende, or augite as the prominent constituents. Varieties may be named according to the characteristic ferromagnesian mineral, as augite-monzonite.

AUGITE-SYENITE (in part). — Essentially the same as augite-monzonite. "Gröba" type of syenite according to Rosenbusch. There may be small amounts of biotite, hypersthene, and hornblende.

AKERITE.[2] — Chiefly potash-feldspar with lime-soda-feldspar, besides biotite, diopside or diopside-ægirite, and a little quartz.

***Sodic Division.*** When there is little or no potash-feldspar the rocks are:

DIORITE[3] (in part). — Chiefly calci-alkalic feldspars, andesine with smaller amounts of oligoclase or labradorite, and sometimes orthoclase or microcline; besides variable amounts of biotite, hornblende, or pyroxene. In some instances a little quartz; in others, much more rarely, a little nephelite. There are also small amounts of iron oxides, titanite, apatite, zircon, and sometimes other minerals. There are rocks called diorite with preponderant soda-calcic feldspar, labradorite, which belong in the next division, III, C, but most diorites are characterized by

[1] de Lapparent, 1864. [2] Brögger, 1890. [3] d'Aubuisson, 1819.

calci-alkalic feldspars whose average composition is andesine. According to the kinds of ferromagnesian minerals that preponderate over one another there are:

MICA-DIORITE. — Chiefly with biotite; HORNBLENDE-DIORITE, or DIORITE proper, chiefly with hornblende; AUGITE-DIORITE, etc. Commonly several kinds of ferromagnesian minerals are present in the same rock, and intermediate varieties between different kinds of diorites abound.

ORNÖITE[1] is a hornblende-diorite of variable composition and texture, occurring on the island Ornö, near Stockholm, Sweden. It has facies rich in hornblende, and others very poor in feldspar, peridotitic.

GABBRO[2] (in part). — Some pyroxene-andesine rocks which belong in this division because of the character of the feldspar, are classed as gabbro because of the pyroxene. They might more properly be called PYROXENE-DIORITE.

ESSEXITE[3] (in part). — Diorite with small amount of nephelite, yielding a dioritic essexite, which is closely related to a nephelite-bearing gabbro, with labradorite.

MALCHITE[4] (in part). — Fine-grained granular rock, sometimes porphyritic, composed of andesine and hornblende. There may be a little quartz, besides magnetite, biotite, etc. Some varieties are aphanitic.

LUCIITE.[5] — Like malchite, with more calcic andesine and less silica.

The *texture* of the more potassic varieties of these rocks is chiefly granular, sometimes with poikilitic development of the potash-feldspar. It may be porphyritic; when the groundmass is fine-grained the rocks become MONZONITE-PORPHYRIES. In the more sodic varieties, the diorites, a prismoid habit of the feldspars is common and characterizes the fabric of the rocks. Fine-grained porphyritic varieties are DIORITE-PORPHYRIES.

*Transitions* to syenite accompany decrease in lime-soda-feldspar; increase in the calcic character of the feldspars leads to gabbro. Increase in quartz produces gradations to quartz-diorite, granodiorite, and granite. With small amounts of nephelite the rocks pass into essexite, or into theralite (in part).

[1] Cederström, 1893. [2] von Buch, 1810. [3] Sears, 1891. [4] Osann, 1892. [5] Chelius, 1892.

(*b*) **Aphanitic Texture,** often porphyritic. LATITES and ANDESITES, and corresponding paleotypal forms. — When these rocks are porphyritic the phenocrysts are chiefly lime-soda-feldspar, labradorite, or andesine, and in some instances also orthoclase or sanidine, often with pyroxene, hornblende, or biotite. The groundmass is chiefly lime-soda-feldspar, andesine, or oligoclase, and sometimes with orthoclase or sanidine, besides pyroxene, iron oxides; less often hornblende, and mica, with smaller amounts of other minerals. The more glassy varieties are often recognized by the phenocrysts and microlites, but can only be definitely identified by chemical analysis. The colors of the rocks are generally darker than aphanitic forms of the preceding division III, A 1 (*b*), trachytes, etc.

*α. Cenotypal Habit*

LATITE.[1] — General name for lava forms of monzonite rocks, that is, chiefly potash-feldspar with lime-soda-feldspar and subordinate amounts of ferromagnesian minerals. Special varieties of latites are:

VULSINITE.[2] — Chiefly potash-feldspar, sanidine, prominent as phenocrysts, with those of lime-soda-feldspar, andesine-labradorite; also augite with some biotite; texture of groundmass trachytic.

CIMINITE.[2] — Chiefly sanidine and labradorite, with augite and olivine. Few phenocrysts of feldspar, more of augite with some of olivine; texture of groundmass characterized in part by small prismoids of lime-soda-feldspars as in andesite; in part by somewhat tabular alkali-feldspar as in trachyte.

TRACHYANDESITE[3] and TRACHYDOLERITE[4] are names sometimes given to vulsinites and ciminites.

BANAKITE.[5] — Chiefly lime-soda-feldspars, andesine, and labradorite, with less sanidine, besides augite and biotite; sometimes a little olivine. Slightly porphyritic, with phenocrysts mostly augite; groundmass characterized by prismoids of lime-soda-feldspar, with outer shell of sanidine.

SHOSHONITE.[5] — Chiefly andesine and labradorite, with sanidine, besides augite and olivine. Phenocrysts of labradorite,

[1] Ransome, 1898. [2] Washington, 1896. [3] Michel-Lévy, 1894. [4] Abich, 1841. [5] Iddings, 1895.

augite, and olivine; groundmass characterized by sanidine as border, or outer shell, to prismoids of lime-soda-feldspar, and also as independent crystals.

MONDHALDEITE.[1] — Phenocrysts of augite, hornblende, bytownite, and some leucite in a glassy groundmass. Chemical composition like that of shoshonite.

ANDESITE[2] (ALEUTITE[3]). — Chiefly andesine, with labradorite or oligoclase, little or no potash-feldspar, besides ferromagnesian minerals, biotite, hornblende, augite, hypersthene; also iron oxides and apatite. There may be a little olivine in some instances; rarely quartz in recognizable crystals. According to the prominent ferromagnesian mineral there are the following kinds of andesite:

PYROXENE-ANDESITE, with hypersthene and augite, AUGITE-ANDESITE, HYPERSTHENE-ANDESITE, HORNBLENDE-PYROXENE-ANDESITE, HORNBLENDE-ANDESITE, HORNBLENDE-MICA-ANDESITE, MICA-ANDESITE. Between these varieties all possible gradations exist, and often several kinds of ferromagnesian minerals occur together. The pyroxene-andesites are generally the most calcic, lowest in silica, and nearest basalt in composition; and the mica-andesites are usually the most alkalic and most siliceous.

Owing to the fact that quartz and orthoclase when present in small amounts are among the last minerals to crystallize, and often remain in the glass base when the rock is not wholly crystallized, and also because the optical behavior of quartz is nearly the same as that of andesine feldspar in thin sections, and since potash feldspar molecules may enter crystals with lime-soda-feldspar molecules when rapidly formed, it follows that the presence of quartz and potash-feldspar in rocks of this general character with glassy or microcrystalline groundmass is usually overlooked, and may be not recognizable. Consequently many rocks are called andesites which actually belong to the more quartzose group II, B 1, (*b*), dacite. Others contain sufficient potash-feldspar to be classed with latites. That is, they are chemically equivalent to quartz-diorite and granodiorite in some instances and to monzonite in others.

VERITE.[4] — Glassy to lithoidal, porphyritic variety of andesite, with phenocrysts of biotite and olivine. The glassy ground-

[1] Graeff, 1900. [2] von Buch, 1836. [3] Spurr, 1900. [4] Osann, 1889.

mass contains microlites of biotite, diopside, and a little feldspar.

SANUKITE.[1] — Glassy hypersthene-andesite, with occasional garnets; without crystals of feldspar. The same rock has been called *boninite.*[2]

MIJAKITE.[3] — A variety of augite-andesite containing a notable amount of manganese, from Mijakeshima, Japan.

BASALT (in part). — Chiefly andesine, with augite or hypersthene and some olivine. Like pyroxene-andesite with olivine; most basalts are characterized by labradorite, and belong in division III, C 1, (*b*).

*β. Paleotypal Habit*

GAUTEITE.[4] — Porphyry having the composition of monzonite. Phenocrysts of labradorite-andesine, often with outer shell of orthoclase; besides hornblende, augite, and biotite, in a groundmass rich in potash-feldspar with trachytic texture.

ANDESITE-PORPHYRY, or PORPHYRITE, having the composition and texture of andesite; sometimes with greater granularity, though microcrystalline; sometimes partly altered. According to the character of the phenocrysts there may be augite-andesite-porphyry or augite-porphyrite, and labradorite-porphyry or labradorite-porphyrite. WEISELBERGITE [5] is a glassy augite-porphyrite.

PROPYLITE.[6] — Andesite with secondary amphibole and often chlorite in place of pyroxene and pyrogenetic hornblende. Usually greenish in color.

The *texture* of these aphanitic rocks varies considerably according to composition and crystallinity, which ranges from holocrystalline to highly glassy. There may be any degree of porphyricity. The fabric of the groundmass may be microgranular or may approach the tabular fabric of trachyte. When chiefly lime-soda-feldspars the microscopic prismoids produce a felt-like or pilotaxitic fabric. Microlitic fabric characterizes the glassy rocks.

*Transitions* to trachyte accompany increase in alkali-feldspars; with additional increase in quartz there are transitions to rhyolite. Increase of quartz alone leads to dellenite and

[1] Weinschenk, 1890. [2] Petersen, 1891. [3] *Idem.* [4] Hibsch, 1897.
[5] Rosenbusch. [6] von Richthofen, 1868.

dacite; increase of olivine and calcic feldspar leads to basalt; and the introduction of nephelite or leucite forms transitions to tephrites.

### B 2. KENTALLENITE, ABSAROKITE, AND MONZONITIC LAMPROPHYRES

Characterized by calci-alkalic feldspars, orthoclase, and lime-soda-feldspars, or andesine alone, with abundant ferromagnesian minerals, augite, hornblende, biotite, olivine. Rocks of this division are not very common, but are probably somewhat more numerous than the more ferromagnesian varieties of the more alkalic group, III, A 2.

(*a*) **Phanerocrystalline Texture.** — KENTALLENITE. — Several varieties of granular rocks belong to this division.

KENTALLENITE.[1] — Chiefly olivine, augite, biotite, lime-soda-feldspar, averaging andesine, and orthoclase. Evenly granular, medium to coarse grained. This is very similar to

OLIVINE-MONZONITE. — Composed of the same minerals as kentallenite, but with feldspar and ferromagnesian minerals in nearly equal proportions.

DURBACHITE.[2] — Chiefly biotite, orthoclase, with lime-soda-feldspar, hornblende, titanite, zircon, and a little quartz. Chemically this rock is closely allied to shoshonites, but the abundance of biotite places it in this division. It has a somewhat porphyritic texture. A similar rock has been called VAUGNERITE.[3]

Some of the rocks called gabbro and orthoclase-gabbro belong in this division, since they contain andesine instead of labradorite and more ferromagnesian minerals than feldspars. They have not been designated by specific names, however.

Certain porphyritic fine-grained rocks having the characteristic composition of these rocks also belong in this phanerocrystalline division, but they bear the same names as the aphanitic varieties described below.

(*b*) **Aphanitic Texture,** often porphyritic, having phenocrysts of ferromagnesian minerals, and few if any of feldspar, MONZONITIC and DIORITIC LAMPROPHYRES.

[1] Hill and Kynaston, 1900. [2] Sauer. [3] Fournet.

*α. Cenotypal Habit*

ABSAROKITE[1] (orthoclase-basalt in part). — Phenocrysts of augite and olivine in a groundmass containing augite, and sometimes biotite, with labradorite-andesine and orthoclase, often forming outer shells around the plagioclase. Rocks of this kind have been described as basalts rich in ferromagnesian minerals, containing some orthoclase in the groundmass.

*β. Paleotypal Habit*

KERSANTITE.[2] — Dark-colored, porphyritic rocks, with aphanitic to fine-grained phanerocrystalline groundmass, chiefly biotite, with hornblende or augite, sometimes olivine, besides lime-soda-feldspar, sometimes with outer shell of orthoclase. The commonest variety is BIOTITE-AUGITE-KERSANTITE. BIOTITE-KERSANTITE and HORNBLENDE-KERSANTITE are less common. An augite-kersantite poor in biotite has been called CUSELITE.[3]

SPESSARTITE.[4] — Lamprophyre composed of hornblende or augite, sometimes with a little olivine, without mica; the feldspar being lime-soda-feldspar, in some instances with outer shell of orthoclase. These rocks are related to quartz-bearing ones.

CAMPTONITE.[5] — Lamprophyre with phenocrysts of hornblende, biotite, augite, with sometimes olivine, in a groundmass of andesine with hornblende and augite. The abundance of hornblende microlites in the groundmass is characteristic. The amphibole is sodic and in part barkevikite, and the rocks are related to nephelite-bearing rocks.

### C I. ANORTHOSITE, GABBRO, BASALT (DIORITE IN PART)

Chiefly soda-calcic feldspar, labradorite, less often bytownite, anorthite, with subordinate amounts of ferromagnesian minerals, augite, enstatite, hypersthene, hornblende, biotite, olivine; besides iron oxides and apatite and sometimes small amounts of orthoclase, quartz, or nephelite.

(*a*) **Phanerocrystalline Texture,** sometimes porphyritic. ANORTHOSITE, GABBRO, DIORITE (in part). — According to the preponderant or characteristic minerals there are:

[1] Iddings, 1895. [2] Delesse, 1851. [3] Rosenbusch, 1887.
[4] *Idem*, 1895. [5] *Idem*, 1887.

ANORTHOSITE.[1] — Almost wholly feldspar, with very small amounts of pyroxene, biotite, hornblende, olivine, iron oxide. Texture commonly equigranular; sometimes tabular with parallel arrangement of the tabular crystals.

KYSCHTYMITE[2] or CORUNDUM-ANORTHOSITE. — The same with notable amounts of corundum.

KEDABEKITE.[3] — Anorthite with lime-iron-garnet and hedengergite.

GABBRO.[4] — Chiefly calcic feldspar, labradorite, bytownite, or anorthite, with variable amounts of pyroxene, diopside, augite or diallage, hypersthene or enstatite; hornblende, biotite, olivine, and small amounts of iron oxide, usually titaniferous magnetite or ilmenite. The proportions of ferromagnesian minerals range from almost nothing in anorthosite to the whole of the rock in peridotites and pyroxenites. The texture is granular, seldom porphyritic. The following varieties have been named:

GABBRO in a restricted sense. — Chiefly soda-calcic feldspars and diallage, with small amounts of other minerals.

OLIVINE-GABBRO. — The same with olivine.

HYPERITE.[5] — Soda-calcic feldspars, with augite, hypersthene, and olivine.

NORITE.[6] — Soda-calcic feldspars, with enstatite or hypersthene. Other minerals may be present in small amounts.

OLIVINE-NORITE. — The same with considerable olivine.

HORNBLENDE-GABBRO. — Soda-calcic feldspars with hornblende. This is called DIORITE by some petrographers.

MICA-GABBRO. — Soda-calcic feldspars and biotite with a little pyroxene, called *mica-diorite* by some.

TROCTOLITE[7] (forellenstein).—Soda-calcic feldspars and olivine.

EUCRITE.[8] — Gabbro whose calcic feldspar is anorthite.

QUARTZ-GABBRO. — Gabbro containing a small amount of quartz.

ESSEXITE[9] (in part). — Chiefly labradorite, with augite, biotite, barkevikitic hornblende, and sometimes olivine; besides a small amount of orthoclase, nephelite, or one of the sodalites.

[1] Sterry-Hunt, 1863. [2] Morozewicz, 1898. [3] Federoff, 1901.
[4] von Buch, 1810. [5] de Beaumont. [6] Esmark.
[7] von Lasaulx, 1875. [8] Rose, 1835. [9] Sears, 1891.

It is a nephelite-orthoclase-bearing gabbro. But some varieties with andesine may be looked upon as nephelite-orthoclase-diorite.

BEERBACHITE[1] (in part). — Fine-grained, granular, rock composed of labradorite and diallage, with variable amounts of hypersthene and magnetite. A fine-grained gabbro, passing into aphanitic forms.

DOLERITE.[2] — Medium to fine-grained rocks sometimes porphyritic, chiefly soda-calcic feldspar, pyroxene and olivine, with magnetite or other iron oxide, having a granular, ophitic, or intersertal fabric. They are phanerocrystalline basalts with cenotypal habit. Those with paleotypal habit are phanerocrystalline diabases. Fine-grained dolerite is sometimes called ANAMESITE.[3]

DIABASE[4] (in part). — Phanerocrystalline rocks called diabase resemble normal pyroxene gabbros in composition but differ from them in fabric. They consist of labradorite and augite, sometimes with diopside, enstatite, or hypersthene, in some varieties with olivine; rarely with small amounts of orthoclase and quartz. The fabric is poikilitic, or ophitic, a particular variety of poikilitic in which the pyroxene acts as a matrix for tabular or bladed crystals of feldspar. In some cases the spaces between the feldspars are filled with small crystals of pyroxene, magnetite, and olivine — an intersertal fabric. Many diabases are somewhat altered and contain chlorite. In some occurrences they have been called THOLEIITE. Aphanitic rocks called diabase resemble basalts.

The *texture* of these rocks is chiefly granular, with the exception of the diabases, in which it is poikilitic, ophitic, or intersertal. Porphyritic texture is not common. When the groundmass is fine-grained the rocks are GABBRO-PORPHYRIES.

*Transitions* to diorites and monzonites take place with increase in alkalic feldspars and with addition of quartz to quartz-diorites and granodiorites. With addition of nephelite, or the sodalites, and orthoclase there are transitions through essexite to nephelite-syenites. Gradations to peridotites, pyroxenites, and hornblendites follow decrease in feldspars and increase in ferromagnesian constituents.

[1] Chelius, 1894. [2] Haüy. [3] von Leonhard, 1823. [4] Brongniart, 1807.

(*b*) **Aphanitic Texture,** often porphyritic. BASALTS, DIABASES, and MELAPHYRES. — Porphyritic varieties of these rocks have phenocrysts of labradorite or more calcic feldspars, augite, and often olivine, seldom hornblende or mica. The groundmass consists of soda-calcic feldspar, pyroxene, magnetite or other iron oxide, and sometimes olivine. In aphanitic rocks of this group olivine is more common than in the phanerocrystalline varieties, and hornblende and biotite less frequent. Quartz occurs in some instances.

*α. Cenotypal Habit*

BASALT.[1] — Chiefly soda-calcic feldspar, augite, diopside, olivine, and magnetite, with hypersthene or enstatite in some instances. Rarely other minerals may be present, and sometimes olivine may be absent. The fabric is often porphyritic, but non-porphyritic varieties are not uncommon. The groundmass is granular in some instances, and ophitic, intersertal, pilotaxitic, or microlitic in others. Mineralogical varieties are:

HYPERSTHENE-BASALT. — With hypersthene, augite, and olivine as the ferromagnesian minerals.

HORNBLENDE-BASALT. — With hornblende rich in iron in addition to the characteristic minerals.

QUARTZ-BASALT. — Having phenocrysts of quartz besides olivine, augite, and soda-calcic feldspar.

HYALOBASALT. — With glassy groundmass. The highly glassy basaltic rocks, usually occurring as thin layers on the margin of bodies of basalt, are TACHYLYTE or HYALOMELAN, and represent basaltic obsidian or perlite.

*β. Paleotypal Habit*

MELAPHYRE.[2] — Basalt more or less altered, having like composition and variations, with secondary minerals, serpentine, chlorite, calcite, etc.

DIABASE (in part). — Essentially the same as basalt in composition, often without olivine, but with a secondary mineral, chlorite or serpentine; frequently with ophitic fabric, and usually not porphyritic; the porphyritic forms being commonly

[1] Ancient name, possibly from Ethiopian *bselt* or *bsalt*, signifying cooked or burnt.

[2] Brongniart, 1813.

called melaphyre. The following mineralogical varieties have been recognized by names:

SALITE-DIABASE (HUNNEDIABASE). — The pyroxene is salite. In some varieties there is a little biotite, hornblende, and quartz.

HYPERSTHENE-DIABASE. — With hypersthene in addition to augite.

PROTEROBASE.[1] — With brown hornblende, biotite, and a little quartz.

QUARTZ-DIABASE (KONGADIABASE). — Similar to the foregoing, with quartz graphically intergrown with feldspar filling spaces between euhedral prismoid or tabular labradorite crystals.

OPHITE.[2] — With uralitized pyroxene.

VARIOLITE.[3] — Spherulitic basaltic rocks of paleotypal habit, with spherulites of feldspar or augite.

The *texture* of these aphanitic rocks varies greatly in different rocks; from porphyritic to non-porphyritic; from holocrystalline to glassy; microgranular, ophitic, intersertal, with various fabrics in the interstitial portions, prismoid, pilotaxitic, and microlitic.

*Transitions* to andesite accompany decrease in the calcic character of the feldspars and in the amount of olivine. With increase in potash-feldspar there is gradation to latites, trachydolerites, etc. With addition of nephelite, sodalites, or leucite the rocks pass into basanite, and with decrease of feldspars and increase in ferromagnesian constituents they grade into limburgites and lamprophyric varieties.

## C 2. ALLIVALITE, GABBRO, AND BASALT (IN PART)

Rocks composed of the same minerals as those characteristic of the gabbro group just described, C 1, but with abundant ferromagnesian minerals, are common, and in only a few cases have been distinguished from those with preponderant soda-calcic feldspars. They are called generally gabbro, in much fewer instances diorite, and the aphanitic forms are usually called basalt, diabase, etc.

(*a*) **Phanerocrystalline Texture.** — GABBRO (in part), diorite (in very small part), diabase (in part).

[1] Gümbel, 1874. [2] Palassou, 1819. [3] Aldrovande, 1648.

ALLIVALITE.[1] — Anorthite and olivine in nearly equal amounts or with a preponderance of anorthite; sometimes small amounts of other minerals, oftenest augite. Texture granular, sometimes with parallel arrangement of tabular feldspars.

HARRISITE.[2] — Preponderant olivine with subordinate anorthite, and sometimes a little pyroxene. The olivine is black, and the rocks are granular, in some cases with a radial arrangement, in others with lamellar intergrowth of the olivine and feldspar. Harrisite and allivalite grade into anorthosite on the one hand and into peridotites on the other.

(*b*) **Aphanitic Texture,** sometimes porphyritic.

*α. Cenotypal Habit*

BASALT (in part). — Containing the same minerals as ordinary basalt, but with preponderant pyroxene and olivine, sometimes with small amount of feldspathoid.

HORNBLENDE-BASALT (in part).

*β. Paleotypal Habit*

DIABASE and melaphyre (in part).

ODINITE.[3] — Small phenocrysts of labradorite and augite, sometimes hornblende, in a groundmass of microscopic prismoids of feldspar and hornblende. GABBRO-LAMPROPHYRE.

### (AB) C 3. PERIDOTITE, PYROXENITE, AND LIMBURGITE

Chiefly ferromagnesian minerals, without feldspar or feldspathoids, or with very small amounts of these minerals. The principal constituents may be pyroxene, diopside, augite, enstatite, or hypersthene, olivine, hornblende, or biotite; in some cases titaniferous magnetite, ilmenite, pyrrhotite, or pyrite; besides smaller amounts of perovskite, picotite, spinel, chromite, garnet, apatite, etc.

These rocks are in most instances related directly through transitions with those of division III, C 2; that is, with sodacalcic feldspar rocks rich in ferromagnesian minerals, and so they are all treated together in this connection. They form subdivision 3 of division III, C. However, some are directly related with nephelite-leucite rocks rich in ferromagnesian minerals; V, A 2, of which they form subdivision 3. And there are

[1] Harker, 1908. [2] Idem, 1908. [3] Chelius, 1892.

probably rocks of this group which bear similar relations to the highly ferromagnesian divisions of other divisions, such as, III, B 2, but if so, they are rare.

(*a*) **Phanerocrystalline Textures,** rarely porphyritic.

PERIDOTITE.[1] — Chiefly olivine, with pyroxene, hornblende, or mica. The olivine is often partly altered to serpentine; frequently completely so. According to the preponderant or characteristic mineral there are the following varieties:

WEHRLITE.[2] — Chiefly olivine and monoclinic pyroxene, diopside, augite, or diallage; sometimes contains hornblende, usually small amounts of chromite and spinel; occasionally chromium-garnet.

EULYSITE.[3] — Wehrlite rich in garnet.

HARZBURGITE,[4] or SAXONITE.[5] — Chiefly olivine and orthorhombic pyroxene, hypersthene, or enstatite (bronzite); sometimes with hornblende and biotite. Commonly contains chromite or picotite; rarely awaruite.

LHERZOLITE.[6] — Chiefly olivine with monoclinic and orthorhombic pyroxenes, diallage (chromdiopside), and bronzite. Commonly with picotite, chromite, spinel, and iron oxide; sometimes garnet, and other minerals.

PICRITE,[7] PICRITE-PORPHYRY. — Chiefly olivine and augite; sometimes with biotite, hornblende, and orthorhombic pyroxene, or a little soda-calcic feldspar; medium to fine-grained texture, sometimes slightly porphyritic. Usually highly altered with abundant serpentine and chlorite.

HORNBLENDE-PICRITE, HORNBLENDE-PERIDOTITE. — Chiefly olivine and hornblende, sometimes with pyroxene and biotite.

CORTLANDTITE.[8] — Chiefly hornblende, poikilitic with smaller crystals of olivine, augite, and hypersthene, sometimes a little feldspar.

SCYELITE.[9] — Chiefly biotite, olivine, and hornblende, with bronzite and chromite.

MICA-PERIDOTITE. — Chiefly olivine and biotite, with much spinel, some ilmenite, and occasionally calcic plagioclase and augite.

[1] Cordier, 1868. [2] Kobell, 1838. [3] Erdmann, 1849.
[4] Rosenbusch, 1887. [5] Wadsworth, 1884. [6] Lelièvre, 1787.
[7] Tschermak, 1866. [8] G. H. Williams, 1886. [9] Judd, 1885.

Kimberlite.[1] — Chiefly olivine, and biotite, with pyroxene, often porphyritic and fine-grained.

Dunite.[2] — Chiefly olivine; sometimes with small amounts of chromite, ilmenite, and pyroxene. Usually evenly granular.

Pyroxenite.[3] — Chiefly pyroxene, with small amounts of olivine, hornblende, iron oxides, spinels, and feldspar. According to the kind of pyroxene there are:

Diallagite, enstatitite (bronzitite), hypersthenite.

Websterite.[4] — A pyroxenite composed of monoclinic and orthorhombic pyroxenes.

Ariégite.[5] — Chiefly monoclinic pyroxene with green spinel. The pyroxene is sometimes diopside or diallage, with a little bronzite. There may also be present hornblende and garnet, yielding mineral varieties of ariégite. Texture evenly granular.

Hornblendite.[6] — Chiefly hornblende, with small amounts of biotite, pyroxene, and olivine; sometimes pyrope.

Pyrrhotite-peridotite. — Chiefly olivine and pyrrhotite, with some labradorite-andesine, hornblende, and magnetite; besides a little chalcopyrite, pyrite, biotite, and spinel. Texture granular, medium to coarse grained.

Magnetite-olivenite. — Chiefly titaniferous magnetite and olivine.

Ilmenite-enstatitite. — Ilmenite and enstatite.

Titaniferous-magnetite rock. — Bodies of iron ore which are segregations or differentiation facies of gabbro magmas.

(*b*) **Aphanitic Texture.** — Rocks having the mineral composition of the peridotites and pyroxenites and an aphanitic texture are rare, partly because magmas of such compositions have seldom solidified under conditions producing aphanitic textures, that is, very rapidly; partly because those that have cooled rapidly as lavas, or as comparatively small-sized bodies, have crystallized into rocks containing appreciable amounts of feldspathic or feldspathoid minerals. That is, certain ferromagnesian minerals occurring in some of the phanerocrystalline forms of these rocks contain enough aluminium to produce notable amounts of feldspars or feldspathoids if it separated independent of the magnesium and iron, which it appears to do in the lava

[1] Carvill Lewis, 1887. [2] von Hochstetter, 1864. [3] Coquand, 1857.
[4] G. H. Williams, 1890. [5] Lacroix, 1900. [6] J. D. Dana, 1880.

forms of these magmas. Thus some rocks which are chemically alike are separated from one another in a strictly mineralogical classification. The rocks placed in this division are in some cases most intimately related to highly ferromagnesian varieties of division V, in which the feldspathic components are chiefly nephelite or leucite; in other cases they are directly related to the phanerocrystalline rocks just described as peridotites and pyroxenites.

*α. Cenotypal Habit*

Rocks of this division are mostly lavas related to nephelite and leucite rocks. They grade into rocks with notable amounts of feldspathoids, which often are called by the same names as those classed here.

LIMBURGITE.[1] — Chiefly olivine and augite, often titaniferous, sometimes with ægirite-augite, magnetite, or ilmenite, rarely hornblende and small amounts of feldspar, nephelite, or haüynite, besides glass base which is partly feldspathic.

AUGITITE.[2] — Like limburgite without olivine. These rocks approach peridotites and pyroxenites in composition and are nearly end products of differentiation of nephelite-syenitic rocks.

*β. Paleotypal Habit.* — Rocks of this division are represented by some picrite-porphyries in which the groundmass is aphanitic. They have been described under Picrite.

## IV. ROCKS CHARACTERIZED BY FELDSPAR AND FELDSPATHOIDS

Nephelite, sodalites, or leucite, with various amounts of ferromagnesian minerals. The relative amounts of feldspars and feldspathoids vary within wide limits, from almost no feldspathoid when the rocks belong to division III to almost no feldspar when the rocks are in division V. According to the character of the preponderant feldspar there are the following groups: A. Chiefly alkalic feldspars, NEPHELITE-SYENITES and PHONOLITES, etc. B. Chiefly calci-alkalic feldspars, THERALITE (in part), and TEPHRITES. C. Chiefly soda-calcic feldspars, BASANITES, and others.

[1] Rosenbusch, 1872. [2] Doelter, 1882.

### A 1. NEPHELITE-SYENITE AND PHONOLITE

Chiefly alkali-feldspar and feldspathoids; that is, orthoclase, microcline, microperthite, soda-orthoclase, soda-microcline (anorthoclase), albite, with nephelite (eleolite), cancrinite, sodalite; rarely haüynite, noselite, or leucite. With these may be combined in some cases a lime-soda-feldspar, more commonly biotite (lepidomelane), various amphiboles and pyroxenes chiefly sodic; besides iron oxides, apatite, zircon, titanite, and garnet; more rarely eudialyte, and in pegmatite rocks låvenite, rosenbuschite, and others.

(*a*) **Phanerocrystalline Texture,** sometimes porphyritic.

NEPHELITE-SYENITE (eleolite-syenite [1]). — General name for any rock having the composition just given, when nephelite (eleolite) is the characteristic feldspathoid.

MUSCOVITE-NEPHELITE-SYENITE. — Commonly pegmatite, of very coarse grain, sometimes with corundum and sodalite; the feldspar is albite in certain instances.

CORUNDUM-NEPHELITE-SYENITE. — Chiefly albite, nephelite, and corundum, with muscovite and sodalite.

MARIUPOLITE.[2] — Chiefly albite in equant anhedrons, with large crystals of nephelite, needles of ægirite, and a little lepidomelane.

LITCHFIELDITE.[3] — Chiefly microcline, albite, nephelite, with lepidomelane, cancrinite, and sodalite. Fine-grained, evenly granular, with streaked heterogeneous character, resembling gneissic texture.

DITROITE.[4] — Chiefly microcline and sodalite, with nephelite, cancrinite, a little wollastonite, besides biotite, hornblende, and other minerals; evenly granular texture. Brögger has applied the term ditroite to all *granular* nephelite-syenites.

SODALITE-SYENITE (in part). — Nephelite-syenite rich in sodalite, 30 to 40 per cent, also containing eudialyte, ægirite, and arfvedsonite. The same name is also used for syenites with little sodalite and no nephelite (p. 363).

CANCRINITE-SYENITE.—Chiefly orthoclase, microcline, (?) albite, with cancrinite, sometimes 29 per cent; less nephelite, ægirite, ægirite-augite, titanite, and apatite.

[1] Blum, 1861.
[2] Morozewicz, 1902.
[3] Bayley, 1892.
[4] Zirkel, 1866.

MIASCITE.[1] — Chiefly alkali-feldspar, nephelite, and biotite, with other minerals in small amount.

FOYAITE.[2] — Chiefly alkali-feldspar, nephelite, and ægirite or ægirite-augite, in some instances with amphibole and biotite and smaller amounts of other minerals. Rosenbusch uses foyaite as a general term for nephelite-syenite, and recognizes pyroxene-foyaites, amphibole-foyaites, mica-foyaites. Brögger uses foyaite for nephelite-syenites with pronounced tabular fabric or trachytoid texture.

LAURDALITE.[3] — Chiefly soda-orthoclase and soda-microcline and nephelite, with lepidomelane and diopside, and small amounts of apatite, titaniferous magnetite, and olivine. Texture coarse-grained, sometimes porphyritic, feldspars with tabular forms that yield crude rhombic sections.

LUJAURITE.[4] — Chiefly alkali-feldspar and nephelite, with eudialyte and considerable ægirite, sometimes arfvedsonite. Texture tabular, often with pronounced parallel arrangement. The ferromagnesian minerals are in relatively small crystals between the feldspars.

PSEUDOLEUCITE-SYENITE. — Chiefly alkali-feldspars, with nephelite or sodalites, and pseudomorphs after leucite, usually consisting of orthoclase and nephelite. Texture granular, somewhat porphyritic, with phenocrysts of pseudoleucite.

BOROLANITE.[5] — Chiefly orthoclase and nephelite, often graphically intergrown, besides melanite, diopside, biotite, titanite, noselite, and iron oxide. Texture granular.

The *texture* of rocks of this group is quite different in different instances, being granular in some varieties, tabular in others; in some cases porphyritic; in some the arrangement of the tabular feldspars is parallel or subparallel, in others diverse. There are aplitic and coarsely pegmatitic varieties. The pronouncedly porphyritic fine-grained forms are called —

NEPHELITE-PORPHYRY. — With nephelite phenocrysts.

PSEUDOLEUCITE-PORPHYRY. — With phenocrysts of pseudoleucite.

RHOMBENPORPHYRY (in part). — Some phanerocrystalline rhombenporphyry contains notable amounts of nephelite.

[1] Rose, (?) 1839. [2] Blum, 1861. [3] Brögger, 1890.
[4] Ramsay, 1894. [5] Teall, 1892.

*Transitions* of these rocks through increase in nephelite or sodalite and decrease of feldspars lead to urtite and sodalite-rock. With decrease of feldspathoids they grade into syenites. With increase of lime-soda-feldspar they pass into theralites and essexites.

(*b*) **Aphanitic Texture,** often porphyritic. PHONOLITE, TINGUAITE. — When porphyritic the chief phenocrysts are sanidine, or soda-microcline and nephelite, or leucite, with fewer of pyroxene, amphibole, biotite, and the sodalites. The groundmass consists of alkali-feldspar, with some feldspathoids, and small amounts of the ferromagnesian minerals, often sodic varieties. Non-porphyritic or very slightly porphyritic varieties are common.

*α. Cenotypal Habit*

PHONOLITE.[1] — Chiefly sanidine or soda-microcline, with nephelite, often sodalite, haüynite, or noselite; very rarely lime-soda-feldspar; diopside, ægirite-augite, ægirite, barkevikite, often melanite, sometimes biotite, olivine. The proportions of feldspar and nephelite vary greatly. Rocks rich in feldspar have a trachytic texture; those rich in nephelite have a nephelinitic texture. Glassy varieties are rare.

APACHITE.[2] — Nephelinitoid phonolite with phenocrysts of feldspar and nephelite surrounded by crystals of ægirite, barkevikitic and arfvedsonitic amphibole, sometimes ænigmatite, producing ocellar fabric, that is, more or less radiating intergrowths with the feldspathic minerals.

LEUCITE-PHONOLITE. — Phonolite containing leucite in addition to the minerals named above, often rich in haüynite, sometimes with melanite, and poor in feldspar. These rocks are also called LEUCITOPHYRE (Rosenbusch). Leucite-phonolite is also defined by Rosenbusch as rocks like phonolite in which nephelite is absent and leucite takes its place. Such rocks are called LEUCITE-TRACHYTE by some petrographers (Zirkel).

*β. Paleotypal Habit*

TINGUAITE.[3] — Chiefly alkali-feldspars; orthoclase, microcline, perthite, soda-microcline, nephelite, with considerable ægirite, and sometimes biotite, leucite, sodalite, and rarer minerals. These

[1] Klaproth, 1801. [2] Osann, 1896. [3] Rosenbusch, 1887.

minerals may be phenocrysts in a groundmass of the same, when the rock is sometimes called TINGUAITE-PORPHYRY.

LEUCITE-TINGUAITE. — Tinguaite in which leucite occurs in place of some of the nephelite, but in all cases studied the leucite is altered either into pseudomorphs or into analcite. The porphyritic varieties have been called LEUCITE-TINGUAITE-PORPHYRY.

NEPHELITE-RHOMBENPORPHYRY. — Rhombenporphyry (p. 364) with notable amounts of nephelite.

*Transitions* of phonolites into trachytes accompany decrease of feldspathoids. With increase in feldspathoids and decrease in feldspars they pass into nephelinites and leucitites, and with increase in lime-soda-feldspars they grade into tephrites. Tinguaites pass into sölvsbergites with decrease of feldspathoids.

### A 2. NEPHELITE-MALIGNITE AND ORENDITE

Rocks composed of the same minerals as those forming nephelite-syenite, but with abundant ferromagnesian minerals, are very rare, and have been found in only a few localities.

(*a*) **Phanerocrystalline Texture.**

NEPHELITE-MALIGNITE. — Chiefly orthoclase and nephelite with ægirite-augite, a little biotite, apatite, and titanite. The feldspathic and ferromagnesian minerals are in about equal proportions.

SHONKINITE (in part). — Some rocks called shonkinite (p. 367) have a notable amount of nephelite and sodalite, and belong to this group.

(*b*) **Aphanitic Texture.**

*α. Cenotypal Habit*

ORENDITE.[1] — Chiefly leucite, sanidine, diopside, and phlogopite, and a small amount of amphibole. An aphanitic rock with many small phenocrysts of phlogopite.

WYOMINGITE.[1] — Chiefly leucite, diopside, phlogopite, and a glass base, probably composed largely of potash-feldspar. Phenocrysts of phlogopite in an aphanitic groundmass, closely related to orendite.

*β. Paleotypal Habit.* — It is probable that some rocks classed as *camptonite* and *monchiquite* belong in this group.

[1] Cross, 1897.

### B I. THERALITE AND TEPHRITE

Chiefly calci-alkalic feldspars, orthoclase with andesine-labradorite, or andesine only, with feldspathoids, nephelite, leucite, and the sodalites, and subordinate amounts of ferromagnesian minerals, pyroxenes, amphiboles, biotite, and olivine. The phanerocrystalline forms of these rocks are rare; the aphanitic varieties more common.

(*a*) **Phanerocrystalline Texture.**

THERALITES.[1] — Chiefly lime-soda-feldspar and nephelite, with diopside, augite, ægirite-augite, less barkevikitic hornblende, a little biotite, olivine, and apatite. The feldspar is properly andesine; varieties with albite belong with nephelite-syenites. With increase in the calcic character of the feldspar the rocks pass into teschenite and essexite. The texture is granular, sometimes slightly porphyritic.

ESSEXITE[2] (in part). — Andesine, with some labradorite and orthoclase; also nephelite or sodalite; besides augite, biotite, sodic hornblende, and sometimes olivine. Texture granular.

(*b*) **Aphanitic Texture.**

*α. Cenotypal Habit*

TEPHRITE.[3] — Chiefly andesine, with oligoclase or labradorite, sometimes sanidine, nephelite, haüynite, and augite, sometimes titaniferous, ægirite-augite, ægirite, less hornblende, and little olivine; rarely melanite, perovskite, and picotite. Often porphyritic, the feldspar phenocrysts being more calcic than those in the groundmass. With increase in olivine tephrites pass into basanite, in which the feldspars are more calcic than in tephrites.

LEUCITE-TEPHRITE. — Chiefly andesine-labradorite and leucite, with nephelite, sodalites, and the same ferromagnesian minerals as in tephrite. With increase in olivine there is transition to leucite-basanite.

KULAITE.[4] — A porphyritic basaltic lava with phenocrysts of hornblende, augite, and olivine in a glassy, microlitic groundmass which contains lime-soda-feldspar and sometimes leucite. Its chemical composition indicates the presence of nephelite. It has also been called HORNBLENDE-BASALT.

[1] Rosenbusch, 1887.
[2] Sears, 1891.
[3] Cordier, 1816.
[4] H. S. Washington, 1900.

*Transitions* from tephrite to phonolite accompany change in feldspars from calci-alkalic to alkalic. There is gradation into latites or trachydolerites with decrease in feldspathoids, and with accession of olivine into basanites.

### B 2. THERALITE IN PART

Rocks of this group with preponderant ferromagnesian minerals have not received specific names as yet, but their occurrence has been noted. In one instance a rock called *theralite* contains 80 per cent of ferromagnesian minerals.

FARRISITE.[1] — An aphanitic rock containing secondary zeolites possibly belongs in this group. It consists of barkevikite and diopside, with small amounts of lepidomelane, olivine, and magnetite, and over 30 per cent of zeolites.

### C 1. TESCHENITE AND BASANITE

Chiefly soda-calcic feldspar, labradorite, with nephelite, leucite, sodalites and pyroxenes, olivine, some amphibole, and biotite.

(*a*) **Phanerocrystalline Texture.** — There are very few rocks that are known to belong in this division.

TESCHENITE.[2] — Chiefly soda-calcic feldspar and analcite, which may be an alteration product from nephelite; also augite, barkevikitic hornblende, some biotite, and apatite. Texture evenly granular, sometimes slightly porphyritic, very similar to theralite.

(*b*) **Aphanitic Texture.**

*α. Cenotypal Habit*

Rocks of this kind are well known among certain volcanic lavas. They are:

BASANITE.[3] — Chiefly labradorite, nephelite, and sodalites with augite, ægirite-augite, and olivine, sometimes barkevikitic hornblende; also apatite, melanite, perovskite, and picotite. Usually porphyritic.

LEUCITE-BASANITE. — Basanite with leucite, often as phenocrysts.

These rocks grade into tephrite and leucite-tephrite with decrease in olivine, and with decrease in feldspar they pass into nephelinite and leucitite. When there is olivine the gradation is into nephelite-basalt and leucite-basalt.

[1] Brögger, 1898. [2] Hohenegger, 1861. [3] Brongniart, 1813.

### C 2. BASANITE IN PART

Rocks of this group with preponderant ferromagnesian minerals have received no special names. They would be classed as basanites.

## V. ROCKS CHARACTERIZED BY FELDSPATHOIDS

Rocks without feldspars, or with very little, having feldspathoids, nephelite, leucite, or the sodalites, together with ferromagnesian minerals. These rocks are not very numerous. Owing to the alkalic character of the feldspathoids they may be placed in the table as in division A with rocks characterized by alkalic feldspars. In the rocks rich in sodic feldspathoids, nephelite, and sodalites, the associated ferromagnesian minerals are usually the sodic varieties, in part at least. In rocks poor in sodic feldspathoids the ferromagnesian constituents are generally not the sodic varieties.

### A 1. URTITE AND SUSSEXITE

(*a*) **Phanerocrystalline Texture.** — Only a few rocks are known to belong to this group, and they are all phanerocrystalline.

URTITE.[1] — Chiefly nephelite, sometimes as much as 86 per cent, with small amounts of ægirite, usually poikilitic, with nephelite; also apatite. Texture evenly granular, medium to fine grained.

SUSSEXITE.[2] — A porphyritic urtite, having phenocrysts of nephelite in a fine-grained to aphanitic groundmass of nephelite and ægirite.

SODALITE-ROCK. — A granular rock consisting almost wholly of sodalite from Kumerngit, Greenland.

TAWITE.[3] — Chiefly sodalite and pyroxene. Texture evenly granular and coarse-grained. Sometimes porphyritic and then called TAWITE-PORPHYRY.

The association of these rocks is with nephelite-syenite, from which they are differentiation products.

(*b*) **Aphanitic Texture.** — There are no proper aphanitic equivalents of the rocks just defined. Most rocks composed of feldspathoids and ferromagnesian minerals are so rich in the latter that they belong to the second division of this group, A 2.

[1] Ramsay, 1896. [2] Brögger, 1894. [3] Ramsay and Hackmann, 1894.

## A 2. IJOLITE, NEPHELINITE, AND MONCHIQUITE

Most of the rocks of division V contain abundant ferromagnesian minerals, chiefly pyroxenes, which are sodic in the more alkalic varieties of the rocks, containing abundant feldspathoids, besides olivine in some instances and mica in others. Magnetite is present in large amounts in some cases. Transitions to rocks composed almost wholly of ferromagnesian minerals occur.

(*a*) **Phanerocrystalline Texture.** — Rocks of this texture are rare, and are mostly associated with nephelite-syenites as extreme products of differentiation. In one case, nephelinite, the rock is usually classed with the aphanitic rocks because most known rocks of like composition are aphanitic, but in certain instances the rock is phanerocrystalline.

IJOLITE.[1] — Chiefly nephelite and pyroxene in nearly equal proportions; besides augite and ægirite-augite, apatite, and titanite; sometimes titaniferous melanite. Texture evenly granular.

NEPHELINITE[2] (in part). — Chiefly nephelite and pyroxene in nearly equal amounts, diopside, ægirite-augite, ægirite, apatite and titaniferous iron oxides, magnetite and ilmenite, and small amounts of many other minerals, sanidine, lime-soda-feldspar, sodalites, leucite, melanite, etc. Very similar to ijolite. Evenly granular rock, grading into aphanitic and porphyritic varieties.

MISSOURITE.[3] — This rock, which is probably the only unaltered phanerocrystalline leucite-bearing rock known, consists of 50.0 augite, 15.0 olivine, 6.0 biotite, 16.0 leucite, 8.0 analcite, and 5.0 apatite and iron oxides. Texture evenly granular, medium to fine grained.

JACUPIRANGITE.[4] — Chiefly titaniferous augite, magnetite, and ilmenite, with nephelite, apatite, and a little perovskite. In some varieties the nephelite nearly equals the other components in amount; in others the iron oxides constitute nearly the whole rock. Evenly granular and medium to fine grained.

(*b*) **Aphanitic Texture,** often porphyritic.

*α. Cenotypal Habit.* — These rocks are the non-feldspathic basalt lavas for the most part, commonly associated with phonolites.

[1] Ramsay and Berghell, 1891.
[2] Cordier, 1868.
[3] Weed and Pirsson, 1896.
[4] Derby, 1891.

NEPHELINITE (in part). — Composition as described above; often porphyritic, with phenocrysts of the chief mineral constituents. In addition to the minerals already named there may be small amounts of basaltic hornblende or katoforite, olivine, melilite, perovskite and picotite.

HAÜYNOPHYRE [1] and NOSEANITE. — Nephelinite in which the nephelite is largely represented by haüynite or noselite.

NEPHELITE-BASALT.[2] — Like nephelinite with notable amounts of olivine. Usually the nephelite is in small amounts.

LEUCITITE.[3] — Chiefly pyroxene, diopside, augite, and ægirite-augite, with leucite and small amounts of sanidine, haüynite, melilite, hornblende, biotite, melanite, perovskite, and chromite. Sometimes porphyritic.

LEUCITE-BASALT. — Composition like that of leucitite with the addition of olivine, and with less feldspathoid constituents. These leucite-rocks are the aphanitic equivalents of missourite.

MADUPITE.[4] — A rock related to wyomingite, composed of diopside, phlogopite, perovskite, and a glass base which is supposed to represent leucite in large part.

MELILITE-BASALT.[5] — Chiefly augite, olivine, and melilite, with magnetite, perovskite, picotite or chromite, and nephelite, sometimes biotite or haüynite. When porphyritic the phenocrysts are augite and olivine. In this rock the feldspathoids are nearly absent and the composition approaches that of the peridotites (A B) C 3.

VENANZITE,[6] EUKTOLITE.[7] — Chiefly olivine, melilite, leucite, and phlogopite, with some magnetite; forming a microcrystalline groundmass with a few phenocrysts of olivine and phlogopite.

*β. Paleotypal Habit.* — Rocks occurring in small bodies, usually as dikes, and generally partly altered.

MONCHIQUITE.[8] — Chiefly augite and barkevikitic hornblende; often with biotite, olivine, and analcite, or a glass base having the composition of analcite. When porphyritic the phenocrysts are hornblende, augite, or biotite.

FOURCHITE.[9] — A monchiquite free from olivine.

[1] Rammelsberg, 1860. [2] Zirkel, 1870. [3] Zirkel, 1870.
[4] Cross, 1897. [5] vom Rath, 1866. [6] Sabatini, 1898.
[7] Rosenbusch, 1899. [8] Rosenbusch and Hunter, 1890. [9] J. F. Williams, 1890.

OUACHITITE.[1] — A fourchite rich in biotite.

ALNÖITE.[2] — A monchiquite rich in olivine and biotite, with melilite and perovskite. Usually porphyritic with large phenocrysts of reddish bronze biotite.

These rocks are readily altered in part, and those so far investigated contain secondary minerals that indicate an easily altered primary feldspathoid, nephelite, analcite, or the sodalites. The rocks are associated with nephelite-syenite, and are lamprophyric facies of these magmas.

[1] Kemp, 1890. [2] Rosenbusch, 1887.

## CHAPTER III

### THE QUANTITATIVE CLASSIFICATION OF IGNEOUS ROCKS[1]

**Introduction.** — The qualitative mineralogical system of classification of igneous rocks has certain inherent serious defects which render it unsatisfactory for exact determination and description of such rocks. Some of these defects will be stated briefly.

On account of its manner of growth from a period of general ignorance of the actual composition of rocks, both chemical and mineral, the present classification and method of definition and of naming rocks are unsystematic. There are few definite, clearly enunciated guiding principles of definition or classification, so that they have become largely subjective, and are capable of being applied differently by different petrographers; with the result often that different names have been applied to the same rock, and in other cases the same name has been given to different rocks.

In some instances present systems of classification involve theories and hypotheses as to origin and formation of rocks which are inadequate or incomplete, and which introduce confusion, uncertainty, and sometimes contradiction into the system.

Owing to the qualitative character of the system in common use certain criteria or components have acquired much greater prominence as a means of classification than they deserve, as is the case with the feldspars and with exceptional, rare minerals in some rocks in which they are very subordinate components.

[1] The statement of the system in this chapter follows closely the text of the first publications of it by Cross, Iddings, Pirsson, and Washington, to which the student is referred for its fuller discussion and for the tables to aid the calculation of norms and modes of igneous rocks, and also for a glossary of the new terms employed in the system. See the *Journal of Geology*, vol. 10, 1902, pp. 555–690; and *Quantitative Classification of Igneous Rocks*. The University of Chicago Press, Chicago, 1903.

The qualitative system frequently classifies rocks on a basis of only part of the constituents, as in the case of some porphyritic rocks, whereby rocks of distinctly different compositions are grouped together, and fundamental relations are confused or ignored.

The present nomenclature of petrography, owing to its unsystematic development and frequent redefinition, is highly unsatisfactory and confusing. It is inadequate to express relationships between different groups of rocks in any system of classification because of the application of similarly formed names to divisions or groups of rocks of very different classificatory significance. Thus *granite* may be applied to rocks of quite different characters, and *rockallite* to a single specific rock which may also be called granite.

In consequence of these and other defects in the qualitative system of classification a new system of classification has been formulated by Cross, Iddings, Pirsson, and Washington which introduces the quantitative element as its basal principle and considers the chemical composition of an igneous rock as its most fundamental character, since it is a quality inherent in the magma before its solidification and is therefore of greatest importance for its correlation with other igneous rocks. In this system all rocks of like chemical composition are classed together in the first instance.

**Basis of Classification.** — The advances made in the knowledge of the composition, texture, and occurrence of igneous rocks, as well as of the nature of solutions and the laws affecting their crystallization and solidification, have justified the consideration of the problem of rock classification in the light of certain established facts of a general nature. The principal facts referred to are the following:

The once molten or liquid condition of the magmas from which igneous rocks have solidified, and the character of such magmas as solutions, and the chemical and physical properties of such solutions.

The possibility of differentiation of complex solutions by known processes, under varying conditions of temperature and pressure, into chemically different bodies, and the resulting variations in chemical composition in rock magmas.

The occurrence of notable chemical variations within igneous masses of small volume in some instances, and the uniformity in the composition of large volumes of rock in others.

The absence of fixed proportions between the chemical constituents of most rocks, and the gradations in chemical and mineral composition of all igneous rocks within certain limits; together with the comparatively small number of important pyrogenetic minerals, and the existence of certain rocks having but one mineral component.

The fact that a complex rock solution may crystallize into different groups of minerals under different conditions, so that rocks composed of different kinds, or different quantities, of minerals may be chemically alike.

The differences in texture which may result from differences in physical conditions attending the crystallization and solidification of rock magmas, and the fact that somewhat similar textures may be developed from chemically different magmas; also the variability in the crystallinity of rocks and the uncrystallized, glassy character of many of them.

The identity of unaltered rocks of different geological ages, and of many rocks that had different modes of occurrence as geological bodies.

And, finally, the fact that while the consanguinity of rocks belonging to one petrographical province is a most fundamental relationship, it is to be treated as a phase of differentiation; and the gradation of one province into others, and the close resemblance, and sometimes the identity, of rocks belonging to various petrographical provinces must lead to the correlation and classification of all igneous rocks from all genetically related groups in one comprehensive system, based upon principles common to igneous rocks in general.

The *inherent characters* of igneous rocks constitute the firmest basis on which to construct a system of classification. This was recognized by the founders of systematic petrography, von Leonhard and Brongniart, and has been admitted by more recent petrographers, but has never been consistently applied to the development of a petrographical system. Of these characters chemical composition is the most fundamental, as already remarked. Mineral composition is almost equally so, if it be

considered in a strict chemical and quantitative manner. But there are instances in which rocks are not completely crystallized, or in which the minerals cannot be identified except by chemical means, owing to their minuteness. Texture follows composition in importance, since it is more variable than mineral composition. These are the three inherent characters by which rocks may be defined, named, and classified without the introduction of theory or hypothesis as to their formation or mode of occurrence.

In establishing a system of divisions or groupings of all known igneous rocks on the basis of these inherent characters it is to be noted that, while the chemical composition is the most fundamental characteristic, there is an absence of stoichiometric proportions among the chemical elements or component oxides. There is no simple relation between them, but serial variations or gradations, and an absence of chemical division lines, or of groups or clusters of similar combinations of elements, as the diagrams, Plates I, II, III, show. It follows, then, that any division of igneous rocks on a purely chemical basis must be arbitrary, unpractical, and unsatisfactory.

On the other hand, most rocks are well characterized by the minerals composing them, by their proportions when compared with one another, and by their individual physical characters, together with their size and shape. Rocks are most readily described and identified by their mineral characteristics. But these cannot be employed by themselves as a basis for a comprehensive and systematic classification of the rocks, partly because some rocks are not holocrystalline but contain more or less glass, and also because some rocks are so fine-grained that the component minerals cannot be identified. Moreover, magma of a given composition may crystallize into different mineral combinations. A classic example of this principle is furnished by the two rocks in Gran, Norway, having almost identical chemical compositions, which crystallized so that one consists almost wholly of alkalic, aluminous hornblende and has been called hornblendite,[1] while the other consists of horn-

[1] Brögger, W. C. Die Eruptivgesteine des Kristiania Gebietes, III, p. 93, Christiania, 1899; and Quar. Jour. Geol. Soc. London, vol. 50, p. 26, 1894. For analyses see also Washington's Tables, p. 345, Nos. 8 and 9.

blende, which is less aluminous, and feldspar, and has been called camptonite. Two other rocks that are almost the same chemically are the nephelite-syenite of Beemerville, N. J.,[1] which consists of orthoclase and nephelite with some ægirite, melanite, and biotite, with very small amounts of other minerals; and the leucite-phonolite of Bracciano, Italy,[2] which has phenocrysts of leucite and ægirite-augite in a groundmass of the same pyroxenes, alkalic feldspar, nephelite, and a little leucite, haüynite, and magnetite. Still other examples may be found upon comparing some quartz-diorites and pyroxene-andesites. At Electric Peak and Sepulchre Mountain, Yellowstone National Park,[3] there are rocks of almost identical chemical compositions which have crystallized, in one case with lime-soda-feldspar, hornblende, biotite, a little pyroxene, orthoclase, and quartz, as quartz-mica-diorite; and in another instance with lime-soda-feldspar, augite, hypersthene, and magnetite, as pyroxene-andesite. From this it is evident that if classed in the first instance on a basis of mineral composition some rocks that are chemically alike would be separated from one another. Nevertheless, whether holocrystalline or vitreous, all igneous rocks may be correlated by considering what mineral combinations may develop from their magmas if completely crystallized. And since various mineral combinations are possible for most magmas, it is necessary to select some one of these combinations as a standard of comparison. And for uniformity and simplicity it is necessary to select the same one for all rocks having like chemical composition. This may be termed the STANDARD MINERAL COMPOSITION, and may or may not correspond to the ACTUAL MINERAL COMPOSITION of a particular rock. The quantitative classification of igneous rocks is based on the chemical composition of the rocks expressed in terms of their standard mineral composition. It is a QUANTITATIVE CHEMICO-MINERALOGICAL CLASSIFICATION.

[1] Bulletin 150, U. S. Geological Survey, 1898, p. 209.

[2] Washington, H. S. Jour. Geol., vol. V, 1897, p. 43.

[3] Iddings, J. P. Twelfth Ann. Rept. U. S. Geological Survey, Washington, 1892, p. 653, and Monograph 32, Part 2, 1899, p. 142 *et seq.*

## STANDARD MINERALS

The reasons for selecting certain pyrogenetic minerals as those best adapted for the classification proposed will appear from a brief consideration of the chemical composition of the important pyrogenetic minerals. These may be arranged in several groups on a basis of their composition and their association in igneous rocks. They are:

A SILICA and ALUMINA UNCOMBINED: quartz (tridymite) and corundum, with zircon, which, though commonly present in small amounts, is oftenest found in rocks rich in silica or the alkalies and alumina.

B. ALUMINOUS NON-FERROMAGNESIAN MINERALS: orthoclase, albite, anorthite, and mixtures of these; also leucite, analcite, nephelite, sodalite, haüynite, noselite, cancrinite, and muscovite.

C. ALUMINOUS FERROMAGNESIAN and CALCIC SILICATES, intermediate between B and D: aluminous pyroxenes and amphiboles, biotite, garnet, tourmaline, melilite, and some spinels.

D. NON-ALUMINOUS FERROMAGNESIAN and CALCIC SILICATES: hypersthene, enstatite, diopside, hedenbergite, acmite, olivine, fayalite, forsterite, and akermanite.

E. NON-SILICEOUS and NON-ALUMINOUS MINERALS and TITANOSILICATES: magnetite, hematite, ilmenite, apatite, titanite, perovskite, fluorite, together with the native metals and certain other metallic oxides and sulphides.

In order to express the chemical composition of a rock in terms of its standard minerals all that are necessary for the expression must be taken into account in their proper proportions. Each standard mineral must be given its correct quantitative value. Owing to the number of standard minerals necessary to express most rocks the arrangement and systematic grouping for purposes of classification is a very intricate problem involving numerous variables, and the most feasible procedure is to recognize such mineral factors in successive groups according to certain degrees of qualities or magnitudes possessed by them when compared with one another. This has been done by grouping the minerals on a basis of chemical resemblance or of recognized associations, and by successively

dividing these groups on a basis of subordinate chemical differences or quantitative values.

For this purpose it is necessary to assemble the minerals chosen as standards into two chemically contrasted groups. These have been made by uniting A and B to form one group and D and E to form the other. The first group contains quartz, corundum, zircon, feldspars, feldspathoids, and muscovite. The second contains hypersthene (and enstatite), diopside (and hedenbergite), acmite, olivine (and fayalite, forsterite) and akermanite, with magnetite, hematite, ilmenite, apatite, and others.

The aluminous ferromagnesian minerals are not included among the standard minerals because of their variable and often complex composition and their variable occurrence. They may be considered as intermediate between groups B and D, and the chemical composition of rocks may be expressed without them by means of the other minerals. Their occurrence in a rock may be expressed by stating the actual mineral composition of the rock.

The two groups of STANDARD MINERALS, together with their simplified dualistic formulæ and the symbols by which they will be subsequently referred to, are as follows:

### GROUP I. SALIC MINERALS

| | | |
|---|---|---|
| Quartz, $SiO_2$ | | Q |
| Zircon, $ZrO_2 \cdot SiO_2$ | | Z |
| Corundum, $Al_2O_3$ | | C |
| Orthoclase, $K_2O \cdot Al_2O_3 \cdot 6\ SiO_2$ | or | F |
| Albite, $Na_2O \cdot Al_2O_3 \cdot 6\ SiO_2$ | ab | F |
| Anorthite, $CaO \cdot Al_2O_3 \cdot 2\ SiO_2$ | an | F |
| Leucite, $K_2O \cdot Al_2O_3 \cdot 4\ SiO_2$ | lc | L |
| Nephelite, $Na_2O \cdot Al_2O_3 \cdot 2\ SiO_2$ (soda-nephelite) | ne | L |
| Kaliophilite, $K_2O \cdot Al_2O_3 \cdot 2\ SiO_2$ | kp | L |
| Sodium chloride, 2 NaCl | sc | L |
| Sodium sulphate, $NaSO_4$ | ss | L |

## Group II. Femic Minerals

| | | | |
|---|---|---|---|
| Acmite, $Na_2O \cdot Fe_2O_3 \cdot 4\ SiO_2$ | ac | P | |
| Sodium metasilicate, $Na_2O \cdot SiO_2$ | ns | P | |
| Potassium metasilicate, $K_2O \cdot SiO_2$ | ks | P | |
| Diopside, $CaO \cdot (Mg,Fe)O \cdot 2\ SiO_2$ | di | P | |
| Wollastonite, $CaO \cdot SiO_2$ | wo | P | |
| Hypersthene, $(Mg,Fe)O \cdot SiO_2$ | hy | P | |
| Olivine, $2\ (Mg,Fe)O \cdot SiO_2$ | ol | O | |
| Akermanite, $4\ CaO \cdot 3\ SiO_2$ | am | O | |
| Magnetite, $FeO \cdot Fe_2O_3$ | mt | H | M |
| Chromite, $FeO \cdot Cr_2O_3$ | cm | H | M |
| Hematite, $Fe_2O_3$ | hm | H | M |
| Ilmenite, $FeO \cdot TiO_2$ | il | T | M |
| Titanite, $CaO \cdot TiO_2 \cdot SiO_2$ | tn | T | M |
| Perovskite, $CaO \cdot TiO_2$ | pf | T | M |
| Rutile, $TiO_2$ | ru | T | |
| Apatite, $3\ (3\ CaO \cdot P_2O_5) \cdot CaF_2$ | ap | A | |
| Fluorite, $CaF_2$ | fr | A | |
| Calcite, $CaO \cdot CO_2$ | cc | A | |
| Pyrite, $FeS_2$ | pr | A | |
| Native metals and other metallic oxides and sulphides | — | A | |

It is necessary to explain at this point three terms which are needed to designate the mineral groups already introduced. Owing to the intricate character of each of these groups recourse was had to mnemonic methods of producing syllables or words for their designation. For group I the word *sal* is used, recalling the *s*iliceous and *al*uminous character of its minerals. For group II *fem* is employed, since its minerals are dominantly *fe*rro*m*agnesian. The corresponding adjectives are *salic* and *femic*. In certain formulæ employed later the words *sal* and *fem* will be used to indicate the minerals of groups I and II, whether they are represented by one or several minerals in any particular instance. The intermediate group, C, of aluminous ferromagnesian and calcic silicates, not standard minerals, will be designated by the terms *alfer* and *alferic*, recalling the

fact that these minerals are characterized by the presence of *al*umina and *fer*ric oxide.

Group I. — The minerals of groups A and B have been united to form the salic group, I, because of the well-known relations between quartz, feldspar, and the feldspathoids and the available silica in magmas, and because of the frequent association of zircon and corundum with the more quartzose and the more feldspathic rocks. It is also in accord with the strong affinities of the basic elements, potassium and sodium, for silicon and aluminium. Kaliophilite is introduced to simplify the expression of certain cases in which silica is extremely low compared with the amount of potassium and other base-forming elements present. Muscovite is omitted in order to simplify the calculation and because it does not form in magmas under certain circumstances. Analcite is omitted for similar reasons, and cancrinite may be considered as nephelite with a slight addition of $CaCO_3$. Sodalite, haüynite, and noselite are omitted from the standard minerals because the determination as well as the manner of occurrence of chlorine and sulphuric oxide in igneous rocks render their calculation uncertain, and make it advisable to express the presence of chlorine and sulphur in terms of sodium chloride and sodium sulphate. Sodalite and noselite were classed as standard minerals in the first publication of the Quantitative System. As the constituents specially characterizing these compounds usually occur in very small amounts, the omission of the minerals named cannot affect materially the statement of the standard minerals.

Group II. — The minerals of groups D and E have been united to form the femic group, II, because of their frequent association in notable amounts in rocks low in silica and alumina and their chemical contrast to minerals of group I. Wollastonite is added in order to simplify the calculation of standard minerals in rocks rich in calcium, where the mineral actually developed is often garnet, an alferic mineral. The simple metasilicates, $Na_2SiO_3$ and $K_2SiO_3$, are introduced for similar reasons. They only appear in certain cases where the alkalies exceed both alumina and ferric oxide, when the actual

mineral formed is probably arfvedsonite or other alkalic aluminous amphibole, an alferic mineral. In like manner *akermanite*, $4\ CaO \cdot 3\ SiO_2$, is introduced to represent the essential components in its isomorphous analogue, *melilite*, whose composition is complex and uncertain.

In order to determine the character and amounts of the standard minerals that express the chemical composition of any rock it is necessary to know the chemical composition and to follow some definite method of calculating the standard minerals from it. The chemical composition may be obtained by chemical analysis of the particular rock, or by calculation from the actual mineral composition of the rock when this has been determined quantitatively by any method, and when the chemical composition of the component minerals is known. Or the chemical composition may be approximated by comparison of the rock with other rocks of similar character which have been chemically analyzed. The method of calculation of the standard minerals from the chemical analysis of the rock is based on certain chemico-mineralogical relations affecting the salic and femic minerals with respect to the relative affinities of the base-forming elements for silicic acid as indicated by frequent associations of pyrogenetic minerals. Owing to the complexity of this problem the statement of it is deferred to a later part of the description of the system, p. 433. The amounts of various mineral components are expressed in terms of mass, and comparisons are made on this basis. It is evident that while at first the classification of igneous rocks must proceed strictly from a study of actual chemical compositions, later on when many kinds of rocks have been accurately described and classified others may be determined by comparison with those already identified which act as types or standards.

## CONSTRUCTION OF THE SYSTEM

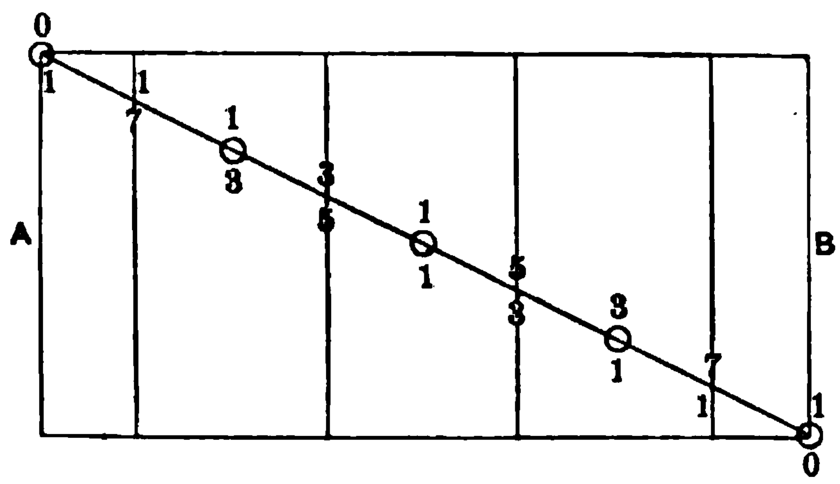
Assuming that the process of determining or calculating the standard minerals from the chemical analyses of rocks is known, the method of classification by their means and the construction of the system may be described without further introduction.

Since there are continuous gradations in composition from rock of one extreme composition to rock of another composition, the chemical and mineral factors involved in the quantitative expressions of all igneous rocks must form series continuous between certain limits. When all cases are considered it is found that the standard mineral constituents exist in all proportions from 0 to 100 per cent, whether considered as part of the whole rock in a given case, or as part of the group of standard minerals to which they may belong. For example, one rock consists wholly of feldspar and another does not contain any; between these extremes there are rocks with all intermediate proportions of feldspar. Similar ranges exist with regard to some of the chemical constituents either with reference to rocks or to mineral groups. Thus the feldspars of one rock may be wholly alkalic, those of another wholly calcic; and between these extremes are all possible gradations. Again, the alkali in the feldspars may be almost wholly potassium in some cases and almost wholly sodium in others; and all possible intermediate mixtures of the two are known to exist.

Under these circumstances, in the absence of natural division lines in such series of factors, it is necessary to establish arbitrary divisions. This has been done by considering certain simple proportions as *center-points* about which variations may be recognized as existing within limits. These limits become the boundaries between petrographical units. As already said, only two factors, or two groups of factors, are compared at any one time, or in the formation of any division in the system. The simplest conceptions of proportions between two factors are: first, one in which either of two factors constitutes the whole and the other is absent; second, that in which both factors are present in equal amounts. Other center-points have been chosen with equal respect to these, that is, midway between the three just mentioned, where the proportion between the two factors is three to one. This furnishes five ideal points. It is to be noted that rocks, or mineral or chemical groups, corresponding to the center-points of these five divisions of any series have no greater value as classificatory types, and are not more important petrologically, or considered quantitatively, than

those occurring in any other part of the system, even those on the boundary between divisions.

This fivefold method of division, which is used throughout the system, may be expressed graphically as follows:




The divisions or petrographical units may be described in terms of factors A and B as:

I. That in which the center-point is where one factor, A, is present alone; A : B : : 1 : 0.

II. That in which the center-point is where one factor, A, is three times the other, B; A : B : : 3 : 1.

III. That in which the center-point is where both factors are present in equal amounts; A : B : : 1 : 1.

IV. That in which the center-point is where one factor, B, is three times the other, A; A : B : : 1 : 3.

V. That in which the center-point is where one factor, B, alone is present; A : B : : 0 : 1.

The dividing lines or boundaries between these center-points occur at the following ratios between A and B: 7: 1, 5 : 3, 3 : 5, 1 : 7. The ranges of the five divisions within which variation between the two factors can exist are given by the expressions

$$\text{I. } \frac{A}{B} > \frac{7}{1}; \quad \text{II. } \frac{A}{B} < \frac{7}{1} > \frac{5}{3}; \quad \text{III. } \frac{A}{B} < \frac{5}{3} > \frac{3}{5}; \quad \text{IV. } \frac{A}{B} < \frac{3}{5} > \frac{1}{7}; \quad \text{V. } \frac{A}{B} < \frac{1}{7}.$$

The divisions may be defined in general terms as:

I. That in which A is present alone or is *extremely* abundant.

II. That in which A *dominates* over B.

III. That in which both A and B are present in *equal* or *nearly equal* amounts.

IV. That in which B *dominates* over A.

V. That in which B is present alone or is *extremely* abundant.

The factor which is extreme or dominant over the other will be spoken of as *preponderant*, the other being *subordinate*. A factor that is present in greater amount than one-eighth of a combined pair of factors, as A when $\frac{A}{B} > \frac{1}{7}$, is said to be *notable*. When it is less than one-eighth of the combined pair it is said to be *negligible*. It is to be noted that the fraction one-eighth relates to a particular group of two factors, not to the rock as a whole, except when the two factors constitute the whole rock. The group itself may represent only a part of the entire rock.

Subdivisions of divisions are made by applying the same fivefold method of division to that factor of a pair which is of sufficient magnitude to be so divided; that is, to one that is *extreme* or *dominant* over the other, or where both are present in *equal* or *nearly equal* amounts. But when one factor is subordinate to another its amount is so small that a fivefold division of it for further discrimination among the rocks characterized and grouped together by it would be unnecessary or over-refined. In this case a threefold division is established by retaining the middle of the fivefold divisions, that is, 3, and by uniting the first and second (1–2) and the fourth and fifth (4–5), in order to prevent confusion of methods. The threefold divisions then are:

1–2.[1] A *preponderates* over B; $\frac{A}{B} > \frac{5}{3}$.

3. A and B are *equal* or *nearly equal;* $\frac{A}{B} < \frac{5}{3} > \frac{3}{5}$.

4–5. B *preponderates* over A; $\frac{A}{B} < \frac{3}{5}$.

[1] In the first publication of the system these threefold divisions are numbered 1, 2, 3, which confuses them with the first three of the fivefold divisions.

When one factor is present in negligible amount, that is, when it is less than one-seventh of the other factor, no subdivision of it is needed.

In order to produce adjective terms to describe the various divisions and subdivisions created in this manner certain prefixes are used in combination with terms indicating the mineral or chemical characteristics of a particular division. To suggest the idea of *extreme*, *per* is used; for *dominant*, *do* or *dom;* for *preponderant*, when a threefold division is used, the prefix is *pre*. When two factors are *equal* or *nearly equal* a compound term is employed, formed by uniting the syllables mnemonic of each factor. Thus with the terms *sal* and *fem* are made the following adjectives: persalic, dosalic, salfemic, dofemic, perfemic.

## DESCRIPTION OF THE QUANTITATIVE SYSTEM

All igneous rocks are classified in divisions and sub-divisions called

CLASS, SUBCLASS.
ORDER, SUBORDER.
RANG, SUBRANG.
GRAD, SUBGRAD.

The words *rang* and *grad* are obsolete forms of rank and grade, and have been introduced to avoid confusion with these words, which are commonly used without any technical significance. These divisions, which are successively smaller, are based on characters of the magma of less and less importance; and homologous divisions throughout the system are based on the same kinds of characters. The various divisions may be briefly described as follows:

CLASSES are based on the relative proportions of the salic and femic minerals in each rock. They are five in number.

SUBCLASSES distinguish between certain mineral subgroups in each of the principal groups, salic and femic.

ORDERS are based on differences in the minerals of the chief subgroup of the preponderant salic or femic group, and serve to distinguish those chemical characters which are dependent on

the dominant acid-forming components of the magma, silicon, titanium, and ferric iron.

SUBORDERS distinguish between several of these components when they are present in considerable amounts, that is, in rocks with much femic minerals.

RANGS are based on the proportions of the base-forming components in the preponderant salic or femic group of minerals; in one case the alkalies and lime, in the other these and magnesia and ferrous oxide.

SUBRANGS distinguish between those components that were grouped together to form a single factor in the treatment of Rangs.

GRADS are based on the relative proportions of the minerals in the subordinate group of femic or salic minerals in each Class. They are analogous to Orders, which treat of the preponderant group in each case.

SUBGRADS distinguish between the base-forming components in the minerals of the subordinate femic or salic groups and are analogous to Rangs in formation.

SECTIONS of any of these divisions are introduced where the number of characteristic components is more than can be recognized by the eight principal divisions just enumerated.

FAMILY. — The term FAMILY should properly be applied to a group of rocks that have been derived by differentiation from some common or parent magma. In its broadest sense it might be applied to all the rocks of one petrographic province. But as there may be genetically related groups of several degrees of consanguinity it is possible there may be need of several distinct terms analogous to Family.

SERIES. — The term SERIES should be applied to groups of rocks characterized by similarity of certain chemical or mineral constituents and by variations in others; the rocks being members of one family. Series may traverse the general system of classification in various directions.

**Classes.** — These, the broadest divisions, express the most general chemico-mineralogical character of magmas, and are based on the relative proportions of the salic and femic mineral groups when calculated in standard minerals for each magma or rock. There are five classes.

CLASS I: $\frac{\text{Sal}}{\text{Fem}} > \frac{7}{1}$, persalic.

This class contains all rocks *extremely* rich in any of the salic minerals — quartz, feldspars, feldspathoids, corundum or zircon.

CLASS II: $\frac{\text{Sal}}{\text{Fem}} < \frac{7}{1} > \frac{5}{3}$, dosalic.

In rocks of this class salic minerals *dominate* over the femic, which are the *subordinate* minerals.

CLASS III: $\frac{\text{Sal}}{\text{Fem}} < \frac{5}{3} > \frac{3}{5}$, salfemic.

In this class occur rocks having salic and femic minerals in *equal* or *nearly equal* amounts..

CLASS IV: $\frac{\text{Sal}}{\text{Fem}} < \frac{3}{5} > \frac{1}{7}$, dofemic.

The femic minerals *dominate* in these rocks, the salic ones being *subordinate.*

CLASS V: $\frac{\text{Sal}}{\text{Fem}} < \frac{1}{7}$, perfemic.

Rocks of this class are *extremely* rich in femic minerals, pyroxenes, olivine, akermanite, magnetite, etc.

**Subclasses.** — These take account of distinctions among the standard minerals constituting the salic and femic groups, which are divided into two parts each. Of the salic minerals, quartz, feldspars, and feldspathoids form a closely associated series when considered petrographically and chemically, and may be contrasted with corundum, zircon, or other salic minerals.

| | | |
|---|---|---|
| Group I | Part 1. | Quartz (Q), feldspars (F), feldspathoids (L). |
| | Part 2. | Corundum (C) and zircon (Z). |

In the group of femic minerals, pyroxene, olivine, akermanite, magnetite, ilmenite, and titanite are closely associated in rocks, and enter frequent transitional series of rocks with different proportions of these minerals. They may be grouped together and contrasted with apatite, fluorite, pyrite, etc.

| | | |
|---|---|---|
| Group II | Part 1. | Pyroxene (P), olivine, and akermanite (O), magnetite, hematite, ilmenite, rutile, perovskite, and titanite (M). |
| | Part 2. | Apatite, flourite, pyrite, etc. (A). |

Subclasses in Classes I, II, and III are made on a fivefold basis by considering the relative proportions of the two parts of the salic group. The reasons for using the salic group instead of the femic in Class III are given in the discussion of Orders. In Classes IV and V subclasses are formed on the proportions of the two parts of the femic group.

In Classes I, II, and III the subclasses are:

SUBCLASS 1, $\frac{QFL}{CZ} > \frac{7}{1}$.

SUBCLASS 2, $\frac{QFL}{CZ} < \frac{7}{1} > \frac{5}{3}$.

SUBCLASS 3, $\frac{QFL}{CZ} < \frac{5}{3} > \frac{3}{5}$.

SUBCLASS 4, $\frac{QFL}{CZ} < \frac{3}{5} > \frac{1}{7}$.

SUBCLASS 5, $\frac{QFL}{CZ} < \frac{1}{7}$.

Distinctions between corundum and zircon may be made in those subclasses in which they are present in notable amount by the formation of SECTIONS as follows:

SECTION 1: $\frac{C}{Z} > \frac{7}{1}$, SECTION 2: $\frac{C}{Z} < \frac{7}{1} > \frac{5}{3}$, etc.

In Classes IV and V the subclasses are:

SUBCLASS 1, $\frac{POM}{A} > \frac{7}{1}$.

SUBCLASS 2, $\frac{POM}{A} < \frac{7}{1} > \frac{5}{3}$.

SUBCLASS 3, $\frac{POM}{A} < \frac{5}{3} > \frac{3}{5}$.

SUBCLASS 4, $\frac{POM}{A} < \frac{3}{5} > \frac{1}{7}$.

SUBCLASS 5, $\frac{POM}{A} < \frac{1}{7}$.

In Classes IV and V Sections of Subclasses may be made when it is necessary to distinguish between apatite and the various metals and sulphides. The method to be followed is similar to that indicated for the Sections distinguishing between corundum and zircon.

It is to be remarked that the vast majority of igneous rocks of all Classes belong to the first Subclass in each Class. There are few rocks known belonging to most of the Subclasses proposed, but if ever found their place in the system is provided for. The remaining description applies in all cases to Subclass 1 in each Class.

**Orders.** — These divisions are based on the relative proportions of the preponderant salic or femic minerals in each Class. In Classes I and II the preponderant minerals are salic, and in Class III salic minerals are considered before femic, although equal in amount, because it is necessary to consider one or the other first, and the salic minerals are probably somewhat more abundant in most rocks of this Class, and being lighter than the femic they are more conspicuous in volume, even when equal in mass. It accords also more nearly with present custom in the qualitative system of classification.

The preponderant salic minerals are those of Part 1, quartz, feldspars, and feldspathoids.

Q = quartz.
F = feldspars, orthoclase, albite, and anorthite.
L = feldspathoids (lenads), leucite, and nephelite.

Since quartz and the feldspathoids (lenads) do not occur together as pyrogenetic minerals, quartz occurring in the more siliceous and the lenads in the less siliceous rocks, these three factors may be employed serially. Consequently in the first three Subclasses of Classes I, II, and III Orders are formed by a double application of the plan of the fivefold division, yielding nine Orders which may be described by adjectives made from syllables mnemonic of quartz, *quar;* of feldspar, *fel;* and of leucite and nephelite, *len.* Moreover, the word *lenad* is introduced for feldspathoid, since this resembles feldspar so closely and is used so frequently in the description of the Quantitative System. The orders just described are:

| | | |
|---|---|---|
| ORDER 1, $\frac{Q}{F} > \frac{7}{1}$, | quartz extreme, | perquaric. |
| ORDER 2, $\frac{Q}{F} < \frac{7}{1} > \frac{5}{3}$, | quartz dominant, | doquaric. |
| ORDER 3, $\frac{Q}{F} < \frac{5}{3} > \frac{3}{5}$, | quartz and feldspar equal or nearly so, | quarfelic. |

ORDER 4, $\frac{Q}{F} < \frac{3}{5} > \frac{1}{7}$, **feldspar dominant over quartz,** **quardofelic.**

ORDER 5, $\frac{Q \text{ or } L}{F} < \frac{1}{7}$, **feldspar extreme,** **perfelic.**

ORDER 6, $\frac{L}{F} < \frac{3}{5} > \frac{1}{7}$, **feldspar dominant over lenad,** **lendofelic.**

ORDER 7, $\frac{L}{F} < \frac{5}{3} > \frac{3}{5}$, **feldspar and lenad equal or nearly so,** **lenfelic.**

ORDER 8, $\frac{L}{F} < \frac{7}{1} > \frac{5}{3}$, **lenad dominant,** **dolenic.**

ORDER 9, $\frac{L}{F} > \frac{7}{1}$, **lenad extreme,** **perlenic.**

In Classes IV and V the dominant femic minerals may be grouped into (1) silicates and (2) nonsilicates with titanosilicates. The silicates may be divided into (*a*) metasilicates and (*b*) lower silicates, yielding

P + O { P. Pyroxenes: diopside, wollastonite, hypersthene, and acmite.
O. Olivine and akermanite. }

M, magnetite, hematite, ilmenite, titanite, etc.

Orders in these classes are formed by comparing the silicates, P + O, with nonsilicates and titanosilicates, M. Descriptive terms have been made from syllables mnemonic of the several subgroups of femic minerals, thus: *pol* to indicate pyroxenes and olivine, including akermanite; *mit* to indicate magnetite, ilmenite, titanite, and other minerals of this subgroup; also *pyr*, denoting pyroxenes, and *ol*, olivine and akermanite.

ORDER 1, $\frac{P + O}{M} > \frac{7}{1}$, femic silicates extreme, perpolic.

ORDER 2, $\frac{P + O}{M} < \frac{7}{1} > \frac{5}{3}$, femic silicates dominant, dopolic.

ORDER 3, $\frac{P + O}{M} < \frac{5}{3} > \frac{3}{5}$, femic silicates and nonsilicates equal or nearly so, polmitic.

ORDER 4, $\frac{P + O}{M} < \frac{3}{5} > \frac{1}{7}$, femic nonsilicates dominant, domitic.

ORDER 5, $\frac{P + O}{M} < \frac{1}{7}$, femic nonsilicates extreme, permitic.

**Sections of Orders.** — In Classes IV and V it is necessary to recognize Sections of Orders to express the proportions between the pyroxene and olivine subgroups in Orders 1, 2, and 3, where polic minerals preponderate, or are equal to the mitic minerals.

| | | |
|---|---|---|
| SECTION 1, | $\frac{P}{O} > \frac{7}{1}$, pyroxene extreme, | perpyric. |
| SECTION 2, | $\frac{P}{O} < \frac{7}{1} > \frac{5}{3}$, pyroxene dominant, | dopyric. |
| SECTION 3, | $\frac{P}{O} < \frac{5}{3} > \frac{3}{5}$, pyroxene and olivine equal or nearly so, | pyrolic. |
| SECTION 4, | $\frac{P}{O} < \frac{3}{5} > \frac{1}{7}$, olivine dominant, | domolic. |
| SECTION 5, | $\frac{P}{O} < \frac{1}{7}$, olivine extreme, | perolic. |

**Suborders.** — In Orders 4 and 5 of Classes IV and V the nonsilicate, mitic minerals preponderate. The subgroups of these minerals most characteristic of rocks belonging to these Orders contain $Fe_2O_3$ and $TiO_2$. The first group includes magnetite and hematite, and is indicated by the symbol H. The second group includes titanite, ilmenite, perovskite, and rutile, and is indicated by T. They may be designated by the syllables *hem* and *til*, mnemonic of the minerals composing them. The Suborders are:

| | | |
|---|---|---|
| SUBORDER 1, | $\frac{H}{T} > \frac{7}{1}$, | perhemic. |
| SUBORDER 2, | $\frac{H}{T} < \frac{7}{1} > \frac{5}{3}$, | dohemic. |
| SUBORDER 3, | $\frac{H}{T} < \frac{5}{3} > \frac{3}{5}$, | tilhemic. |
| SUBORDER 4, | $\frac{H}{T} < \frac{3}{5} > \frac{1}{7}$, | dotilic. |
| SUBORDER 5, | $\frac{H}{T} < \frac{1}{7}$, | pertilic. |

Having recognized the acid-forming elements that characterize preponderant minerals in rocks in the formation of Classes and Orders, the base-forming elements in these minerals are recognized in the formation of the succeeding divisions, Rangs and Grads.

**Rangs.** — The general character of the base-forming elements in the minerals preponderating in each Order of the five

Classes is the basis for the formation of Rangs. For salic minerals this is expressed by the terms *alkalic* and *calcic*, which relate to the feldspars and lenads. Comparison is made between the proportions of molecules of $K_2O' + Na_2O'$ and $CaO'$ in the salic minerals, $K_2O'$, $Na_2O'$, and $CaO'$, being the portions of these components allotted to salic minerals, those allotted to the femic minerals being designated by $K_2O''$, $Na_2O''$, and $CO''$. The divisions for Rangs in Classes I, II, and III are fivefold, as follows:

| | | |
|---|---|---|
| RANG 1, | $\frac{K_2O' + Na_2O'}{CaO'} > \frac{7}{1}$, | peralkalic. |
| RANG 2, | $\frac{K_2O' + Na_2O'}{CaO'} < \frac{7}{1} > \frac{5}{3}$, | domalkalic. |
| RANG 3, | $\frac{K_2O' + Na_2O'}{CaO'} < \frac{5}{3} > \frac{3}{5}$, | alkalicalcic. |
| RANG 4, | $\frac{K_2O' + Na_2O'}{CaO'} < \frac{3}{5} > \frac{1}{7}$, | docalcic. |
| RANG 5, | $\frac{K_2O' + Na_2O'}{CaO'} < \frac{1}{7}$, | percalcic. |

In Order 6, in which feldspar is dominant over lenads, only the first four Rangs may occur; in Order 7 only the first three; in Order 8 only the first two; and in Order 9 only the first one. This is because there is no calcium in the lenads, when these are only normative leucite and nephelite.

For femic minerals the general chemical character of the base-forming elements is expressed as *ferromagnesian*, *calcic*, or *alkalic*. It is necessary to combine two of these in order to form two contrasted factors instead of three. This is done by uniting the first two and comparing the ferromagnesian and calcic with the alkalic components of the femic minerals; that is, $MgO + FeO + CaO''$ with $K_2O'' + Na_2O''$. The mnemonic term indicating the first factor is *mirlic*, referring to magnesium, iron, and lime. A fivefold division is established as in other divisions, but rocks representing the more alkalic Rangs in Classes IV and V are not known. The Rangs are:

| | | |
|---|---|---|
| RANG 1, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} > \frac{7}{1}$, | permirlic. |
| RANG 2, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} < \frac{7}{1} > \frac{5}{3}$, | domirlic. |

And so on if needed.

**Sections of Rangs** are necessary in Classes IV and V to distinguish between the *ferromagnesian* and *calcic* characters of femic minerals. Iron and magnesium are grouped together because they are commonly closely associated in femic minerals and behave somewhat independently of calcium. The syllable mnemonic of magnesium and iron is *mir*, and the following Sections of Rangs have been established:

| | | |
|---|---|---|
| SECTION 1, | $\frac{(Mg,Fe)O}{CaO''} > \frac{7}{1}$, | permiric. |
| SECTION 2, | $\frac{(Mg,Fe)O}{CaO''} < \frac{7}{1} > \frac{5}{3}$, | domiric. |
| SECTION 3, | $\frac{(Mg,Fe)O}{CaO''} < \frac{5}{3} > \frac{3}{5}$, | calcimiric. |
| SECTION 4, | $\frac{(Mg,Fe)O}{CaO''} < \frac{3}{5} > \frac{1}{7}$, | docalcic. |
| SECTION 5, | $\frac{(Mg,Fe)O}{CaO''} < \frac{1}{7}$, | percalcic. |

**Subrangs.** — These distinguish between the chemical characters grouped together in one of the factors used for Rangs, the alkalic in one set of cases, ferromagnesian in another. In Classes I, II, and III the proportions of the salic alkalies, potash and soda, need to be distinguished, which is done as follows:

| | | |
|---|---|---|
| SUBRANG 1, | $\frac{K_2O'}{Na_2O'} > \frac{7}{1}$, | perpotassic. |
| SUBRANG 2, | $\frac{K_2O'}{Na_2O'} < \frac{7}{1} > \frac{5}{3}$, | dopotassic. |
| SUBRANG 3, | $\frac{K_2O'}{Na_2O'} < \frac{5}{3} > \frac{3}{5}$, | sodipotassic. |
| SUBRANG 4, | $\frac{K_2O'}{Na_2O'} < \frac{3}{5} > \frac{1}{7}$, | dosodic. |
| SUBRANG 5, | $\frac{K_2O'}{Na_2O'} < \frac{1}{7}$, | persodic. |

In Rangs 4 and 5 of Classes I, II, and III, because of the subordinate amounts of the alkalies, only three divisions are used.

| | | |
|---|---|---|
| SUBRANG 1–2, | $\frac{K_2O'}{Na_2O'} > \frac{5}{3}$, | prepotassic. |
| SUBRANG 3, | $\frac{K_2O'}{Na_2O'} < \frac{5}{3} > \frac{3}{5}$, | sodipotassic. |
| SUBRANG 4–5, | $\frac{K_2O'}{Na_2O'} < \frac{3}{5}$, | presodic. |

In Classes IV and V the variable chemical quality is in the ferromagnesian content. The alkalies are preponderantly sodic, and there is no need of subdivisions to discriminate between the alkalies. In Sections 1 and 2 of Rangs 1 and 2 there are the following subrangs:

| | | |
|---|---|---|
| SUBRANG 1, | $\frac{MgO}{FeO} > \frac{7}{1}$, | permagnesic. |
| SUBRANG 2, | $\frac{MgO}{FeO} < \frac{7}{1} > \frac{5}{3}$, | domagnesic. |
| SUBRANG 3, | $\frac{MgO}{FeO} < \frac{5}{3} > \frac{3}{5}$, | magnesiferrous. |
| SUBRANG 4, | $\frac{MgO}{FeO} < \frac{3}{5} > \frac{1}{7}$, | doferrous. |
| SUBRANG 5, | $\frac{MgO}{FeO} < \frac{1}{7}$, | perferrous. |

In Section 3 of Rangs 1 and 2 and in other Rangs of Classes IV and V only three divisions are used because of the subordinate amount of miric component.

| | | |
|---|---|---|
| SUBRANG 1–2, | $\frac{MgO}{FeO} > \frac{5}{3}$, | premagnesic. |
| SUBRANG 3, | $\frac{MgO}{FeO} < \frac{5}{3} > \frac{3}{5}$, | magnesiferrous. |
| SUBRANG 4–5, | $\frac{MgO}{FeO} < \frac{3}{5}$, | preferrous. |

Owing to the omission of the sodalites from the list of standard minerals there is no need of Sections of Subrangs, which were described in the first publication of the Quantitative System of Classification of igneous rocks.

By the divisions so far established the dominant features of the preponderant salic or femic minerals have been recognized, and the corresponding chemical and mineral differences in igneous rocks have been provided for. There remain those differences that are expressed by the subordinate standard minerals, femic on the one hand, salic on the other.

In Classes I and V the subordinate groups of standard minerals are so small as to be negligible, so that no further division of these Classes is necessary.

In Classes II and IV, the subordinate groups of minerals being less abundant than the preponderant, a threefold division

is sufficient, at least for present requirements, whereas in Class III the second group, femic, is equal or nearly so to the one first considered, salic; so a fivefold division in this case is desirable.

**Grads.** — These are based on the proportions of the standard minerals of the subordinate group in each Class, where Grads are employed, and the method of treatment is like that used in the treatment of the preponderant groups.

In Class II the subordinate group is femic and a threefold division yields

| | | |
|---|---|---|
| Grad 1–2, | $\frac{P+O}{M} > \frac{5}{3}$, | prepolic. |
| Grad 3, | $\frac{P+O}{M} < \frac{5}{3} > \frac{3}{5}$, | polmitic. |
| Grad 4–5, | $\frac{P+O}{M} < \frac{3}{5}$, | premitic. |

In Class III the femic group is as important as the salic and is susceptible of fivefold division, yielding

| | | |
|---|---|---|
| Grad 1, | $\frac{P+O}{M} < \frac{7}{1}$, | perpolic. |
| Grad 2, | $\frac{P+O}{M} < \frac{7}{1} > \frac{5}{3}$, | dopolic. |
| Grad 3, | $\frac{P+O}{M} < \frac{5}{3} > \frac{3}{5}$, | polmitic. |
| Grad 4, | $\frac{P+O}{M} < \frac{3}{5} > \frac{1}{7}$, | domitic. |
| Grad 5, | $\frac{P+O}{M} < \frac{1}{7}$, | permitic. |

In this Class it is necessary to discriminate between pyroxene and olivine which may be done in a threefold manner, yielding Sections of Grads as follows:

| | | |
|---|---|---|
| Section 1–2, | $\frac{P}{O} > \frac{5}{3}$, | prepyric. |
| Section 3, | $\frac{P}{O} < \frac{5}{3} > \frac{3}{5}$, | pyrolic. |
| Section 3–4, | $\frac{P}{O} < \frac{3}{5}$, | preolic. |

In Class IV the subordinate minerals are salic, and as they are in smaller amounts than the femic a threefold division

applied in series is sufficient, yielding five divisions instead of the nine used in making Orders.

| | | |
|---|---|---|
| GRAD 1–2, | $\frac{Q}{F} > \frac{5}{3}$, | prequaric. |
| GRAD 3, | $\frac{Q}{F} < \frac{5}{3} > \frac{3}{5}$, | quarfelic. |
| GRAD 4–5–6, | $\frac{Q \text{ or } L}{F} < \frac{3}{5}$, | prefelic. |
| GRAD 7, | $\frac{L}{F} < \frac{5}{3} > \frac{3}{5}$, | lenfelic. |
| GRAD 8–9, | $\frac{L}{F} > \frac{5}{3}$, | prelenic. |

**Subgrads.** — These are based on the general chemical character of the base-forming elements in the minerals employed to form Grads, and bear the same relation to Grads that Rangs bear to Orders. The forms of expression are similar to those used in Rangs and need no further comment. In Classes II and IV the division is threefold.

In Class II, the subordinate minerals being femic, the divisions are:

| | | |
|---|---|---|
| SUBGRAD 1–2, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} > \frac{5}{3}$, | premirlic. |
| SUBGRAD 3, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} < \frac{5}{3} > \frac{3}{5}$, | alkalimirlic. |
| SUBGRAD 4–5, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} < \frac{3}{5}$, | prealkalic. |

In Class III, the mineral group treated second is femic, and because of its abundance the division is fivefold, yielding

| | | |
|---|---|---|
| SUBGRAD 1, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} > \frac{7}{1}$, | permirlic. |
| SUBGRAD 2, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} < \frac{7}{1} > \frac{5}{3}$, | domirlic. |
| SUBGRAD 3, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} < \frac{5}{3} > \frac{3}{5}$, | alkalimirlic. |
| SUBGRAD 4, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} < \frac{3}{5} > \frac{1}{7}$, | domalkalic. |
| SUBGRAD 5, | $\frac{(Mg,Fe)O + CaO''}{K_2O'' + Na_2O''} < \frac{1}{7}$, | peralkalic. |

In Class IV the subordinate minerals are salic and the division threefold, yielding:

SUBGRAD 1–2, $\frac{K_2O' + Na_2O'}{CaO'} > \frac{5}{3}$, prealkalic.

SUBGRAD 3, $\frac{K_2O' + Na_2O'}{CaO'} < \frac{5}{3} > \frac{3}{5}$, alkalicalcic.

SUBGRAD 4–5, $\frac{K_2O' + Na_2O'}{CaO'} < \frac{3}{5}$, precalcic.

**Sections of Subgrads** in Class III are necessary to further discriminate between the characteristic chemical constituents in the femic minerals because of the amounts of these minerals that may be present in rocks of this Class. There is also need of Subsections. The following have been established, corresponding to Sections and Subsections of Rangs in Classes IV and V:

In Rangs 1, 2, and 3 of Class III, in Subgrads 1, 2, 3, and 4:

SECTION 1–2, $\frac{(Mg,Fe)O}{CaO''} > \frac{5}{3}$, premiric.

SECTION 3, $\frac{(Mg,Fe)O}{CaO''} < \frac{5}{3} > \frac{3}{5}$, calcimiric.

SECTION 4–5, $\frac{(Mg,Fe)O}{CaO''} < \frac{3}{5}$, precalcic.

And

SUBSECTION 1–2, $\frac{MgO}{FeO} > \frac{5}{3}$, premagnesic.

SUBSECTION 3, $\frac{MgO}{FeO} < \frac{5}{3} > \frac{3}{5}$, magnesiferrous.

SUBSECTION 4–5, $\frac{MgO}{FeO} < \frac{3}{5}$, preferrous.

The system just described provides more divisions than are needed for the igneous rocks at present known. In some instances still smaller divisions seem already desirable. Such can be supplied by further subdivision, according to the method just employed, by recognizing other chemical characters or components, or by increasing the number of divisions or center-points in any part of the system.

## NORM AND MODE

The classification so far developed is strictly one of rock magmas, being based on their chemical composition and the possible mineral composition expressed in terms of standard minerals. It does not take into consideration to what extent they may be crystalline or glassy and what may be the actual minerals

developed in them. The chief purpose of the classification up to this point is to bring together all igneous rocks of like chemical composition into the same divisions or groups. The rocks as distinguished from magmas involve the actual mineral composition and the texture in each case, and, while these factors are so related to the chemical composition of the magma and the physical conditions under which solidification took place that they must be strictly interdependent, the relationship appears to be so complex that it is not possible at present to express it in a comprehensive system of classification. Therefore these factors have been treated separately and employed as qualifiers of the magmatic units established by the system just described. That is, the name given to the magmatic unit is qualified by compounding it with terms indicating the actual mineral composition of the rock and others indicating its texture.

In discussing the relations between the actual mineral composition of rocks and their calculated composition in standard minerals and the extent to which qualifying compound terms may be necessary, two terms of general significance have been introduced. For the calculated *standard mineral composition* of a rock the term NORM is used, and for the *actual mineral composition*, quantitatively determined, the term MODE is used. The standard minerals constituting the norm are called the NORMATIVE minerals, that is, those which establish or set up a norm. It is to be noted that this is quite different from the term *normal*, which, as ordinarily used, means usual or common. *Normative* minerals are frequently not the normal ones in certain rocks, though they may be the normal minerals in many others.

**Normative Modes.** — When the mode of a rock is essentially the same as its norm there is no need of qualifying the magmatic name, because it already indicates the actual mineral composition. The mode may be said to be normative, and a NORMATIVE MODE may be defined as one in which the actual mineral composition is so nearly the same as the standard mineral composition calculated from the analysis of the rock that either may be used to classify the rock correctly.

In comparing actual and standard minerals the lime-soda-feldspars and soda-potash-feldspars are treated as though compounded of albite, anorthite, and orthoclase, and are not

reckoned as different from the calculated simple molecules except as they may differ quantitatively. They may be treated as normative unless it is desired to express in the name the particular combination of feldspar molecules represented in the mode.

In many rocks having rather simple mineral compositions the correspondence between the mode and norm is nearly complete. This is true of the great majority of holocrystalline rocks of Class I and the greater portion of those in Class II. And these two classes comprise over three-quarters of the analyzed igneous rocks of the earth. The accord between mode and norm is close for many rocks in Class V, but is least for rocks in Classes III and IV.

**Abnormative Modes.** — When there is a notable difference between mode and norm in any rock the mineral or minerals causing the difference may be called ABNORMATIVE minerals. They may be standard minerals, that is, salic or femic, or they may be alferic minerals. Such modes are ABNORMATIVE. The minerals whose presence renders a mode abnormative may be called the CRITICAL ones. When the exact chemical character and amount of the critical minerals in an abnormative mode are known the norm of the rock may be calculated from them.

**Varieties.** — When there are quite subordinate minerals present in a rock, either normative or abnormative, which it is desirable to recognize as distinguishing features of the rock, the subdivision of any classificatory division necessary to express the idea is a VARIETY. There may be *normative varieties* and *modal varieties*. Thus some perfelic rocks of Class I may contain negligible but significant amounts of nephelite, others may contain similarly small amounts of quartz, and it may be desirable to recognize these differences. Rocks with normative modes may contain very small amounts of hornblende or of biotite. The presence of small amounts of rare minerals also, such as columbates or phosphates, may be recognized as forming modal varieties.

**Indeterminable Modes.** — Rocks that are partly glassy or, because of the minuteness of some of their component crystals, do not permit the quantitative determination of all the component minerals, have INDETERMINABLE MODES. Their classification must rest upon a chemical analysis of the rock or on a comparison of the rocks with a similar one that has been analyzed.

**Texture.** — The texture of igneous rocks, which is one of their most characteristic features and which becomes a qualifying factor in the nomenclature, has been discussed at length in Chapter VI of Part I, and needs no further comment in this place. The method of introducing it into the nomenclature will be described later on.

## NOMENCLATURE.

The Quantitative System of Classification here proposed, being based on relations and principles distinct from those used in the Qualitative Mineralogical System, requires a distinctly different nomenclature, because the new divisions do not express the same conceptions or characters as those inherent in the old ones. And the use of an old name with a new meaning is to be avoided, since it leads to serious confusion and misunderstanding, as is fully illustrated by the usage of terms in the qualitative system.

**Magmatic Names.** — In order to provide names that may distinguish between the different degrees of divisions in the quantitative system, and thus remedy a defect in the present qualitative nomenclature, words have been made by uniting a distinctive termination to a root or body term which stands for the magma, or group or range of magmas, in each division of the system. These MAGMATIC NAMES must be qualified by mineral and textural terms to indicate a particular rock.

TERMINATIONS for names in different divisions have been selected as follows:

| | |
|---|---|
| Class, — **ane.** | Subclass, — **one.** |
| Order, — **are.** | Suborder, — **ore.** |
| Rang, — **ase.** | Subrang, — **ose.** |
| Grad, — **ate.** | Subgrad, — **ote.** |

It is to be noted that the distinctive consonants are in their alphabetical order, *n*, *r*, *s*, *t*, which may help in associating them with the division of the system to which they have been assigned. The vowel *a* is changed to *o* in the subdivision of each principal division. For the name of a Section of a principal division, or a subdivision, the letter *i* is introduced before the proper termination for the division.

ROOT. — The root of the name is in some cases one or more syllables mnemonic of certain characters of the magmatic division, or it is derived from a locality, or it may be chosen arbitrarily. The use of mnemonics, while an aid to the memory

when simple in form, becomes impracticable when the form is highly complex. In the selection of roots to form names for divisions not yet named it is suggested that they be adjusted to the relative position of the division to which they are to be applied, that is, where names in present use are to be transformed into those of the quantitative system by changing the termination. Names that have been applied to groups of rocks should be used for larger magmatic divisions, and those given to specific rocks should be given to smaller magmatic divisions. Moreover, rocks upon which a new name is based should be unaltered and well analyzed. A locality root should be used if possible, and it should be as short as reasonable. The rock upon which a new term is based should be as near as possible the center of a division and not near the boundary between two divisions.

A rock whose composition is such that its magma occurs near the boundary between two magmatic divisions should receive a compound magmatic name composed of the magma names for these two divisions of the system, that in which the rock magma occurs being placed second.

The names of the five Classes are compounded of the mnemonic syllables *sal* and *fem*, the prefixes corresponding to the relative proportions of the two primary groups of standard minerals, and the proper termination.

| | | |
|---|---|---|
| CLASS I, | PERSALANE: | extremely salic, $\frac{\text{Sal}}{\text{Fem}} > \frac{7}{1}$. |
| CLASS II, | DOSALANE: | dominantly salcic, $\frac{\text{Sal}}{\text{Fem}} < \frac{7}{1} > \frac{5}{3}$. |
| CLASS III, | SALFEMANE: | equally salic and femic, $\frac{\text{Sal}}{\text{Fem}} < \frac{5}{3} > \frac{3}{5}$. |
| CLASS IV, | DOFEMANE: | dominantly femic, $\frac{\text{Sal}}{\text{Fem}} < \frac{3}{5} > \frac{1}{7}$. |
| CLASS V, | PERFEMANE: | extremely femic, $\frac{\text{Sal}}{\text{Fem}} < \frac{1}{7}$. |

Names for other divisions are derived from those of geographical localities. Owing to their number they have been placed in tables where their significance and definitions may be made out. They do not need specific definition.[1]

[1] A Glossary of new names and words employed in the Quantitative System will be found in the publication, Quantitative Classification of Igneous Rocks, by Cross, Iddings, Pirsson, and Washington. The University of Chicago Press, 1903.

| ORDER | 1. $\frac{Q}{F} > \frac{7}{1}$ VICTORARE. | 2. $\frac{Q}{F} < \frac{7}{1} > \frac{5}{3}$ BELGARE. | 3. $\frac{Q}{F} < \frac{5}{3} > \frac{3}{5}$ COLUMBARE. |
|---|---|---|---|
| RANG 1. PERALKALIC, $\frac{K_2O+Na_2O}{CaO} > \frac{7}{1}$ | ............ | 1. *Dargase* | 1. *Alaskase* |
| Subrang 1. Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$ | ............ | x | 1. x |
| Subrang 2. Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$ | ............ | x | 2. Magdeburgose |
| Subrang 3. Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | ............ | x | 3. Alaskose |
| Subrang 4. Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$ | ............ | ............ | 4. Taurose |
| Subrang 5. Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$ | ............ | ............ | 5. Westphalose |
| RANG 2. DOMALKALIC, $\frac{K_2O+Na_2O}{CaO} < \frac{7}{1} > \frac{5}{3}$ | ............ | 2. x | 2. *Alsbachase* |
| Subrang 1. Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$ | ............ | 1-2. x | 1............ |
| Subrang 2. Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$ | ............ | | 2. Mihalose |
| Subrang 3. Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | ............ | 3. x | 3. Tehamose |
| Subrang 4. Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$ | ............ | 4-5. x | 4. Alsbachose |
| Subrang 5. Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$ | ............ | | 5. Yukonose |
| RANG 3. ALKALICALCIC, $\frac{K_2O+Na_2O}{CaO} < \frac{5}{3} > \frac{3}{5}$ | ............ | 3. x | 3. *Riesenase* |
| Subrang 1. Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$ | ............ | 1-2...... | 1............ |
| Subrang 2. Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$ | ............ | | 2. x |
| Subrang 3. Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | ............ | 3. x | 3. Riesenose |
| Subrang 4. Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$ | ............ | 4-5 x | 4. x |
| Subrang 5. Persodic $\frac{K_2O}{Na_2O} < \frac{1}{7}$ | ............ | | 5. Vulcanose |
| RANG 4. DOCALCIC, $\frac{K_2O+Na_2O}{CaO} < \frac{3}{5} > \frac{1}{7}$ | ............ | ............ | 4. x |
| Subrang 1-2. Prepotassic, $\frac{K_2O}{Na_2O} > \frac{5}{3}$ | ............ | ............ | 1-2 x |
| Subrang 3. Sodipotassic. $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | ............ | ............ | 3. x |
| Subrang 4-5. Presodic, $\frac{K_2O}{Na_2O} < \frac{3}{5}$ | ............ | ............ | 4-5............ |
| RANG 5. PERCALCIC, $\frac{K_2O+Na_2O}{CaO} < \frac{1}{7}$ | ............ | ............ | ............ |

NOTE. — X indicates that analyses are known which belong to this division, but that no
The $K_2O$, $Na_2O$ and CaO in these ratios are only those in the salic minerals.

Subclass II is represented by Section 1, $\frac{C}{Z} > \frac{7}{1}$, corundum-bearing rocks, which occur
Rang 1, Uralase; Subrang 3, Uralose; and Rang 4, Borsowase; Subrang 3, Borsowose

| 4. $\frac{Q}{F} < \frac{3}{5} > \frac{1}{7}$ BRITANNARE. | 5. $\frac{Q, L}{F} < \frac{1}{7}$ CANADARE. | 6. $\frac{L}{F} < \frac{3}{5} > \frac{1}{7}$ RUSSARE. | 7. $\frac{L}{F} < \frac{5}{3} > \frac{3}{5}$ TASMANARE. | 8. $\frac{L}{F} < \frac{7}{1} > \frac{5}{3}$ ONTARARE. | 9. $\frac{L}{F} > \frac{7}{1}$ x |
|---|---|---|---|---|---|
| 1. *Liparase* | 1. *Nordmarkase* | 1. *Miaskase* | 1. *Laugenase* | 1............. | 1........ |
| 1. Lebachose | 1............. | 1............. | 1............. | ............. | ......... |
| 2. Omeose | 2............. | 2............. | 2............. | ............. | ......... |
| 3. Liparose | 3. Phlegrose | 3. Beemerose | 3. Appianose | ............. | ......... |
| 4. Kallerudose | 4. Nordmarkose | 4. Miaskose | 4. Laugenose | ............. | ......... |
| 5. Noyangose | 5. Tuolumnose | 5. Mariupolose | 5............. | ............. | ......... |
| 2. *Toscanase* | 2. *Pulaskase* | 2. *Viezzenase* | ............. | 2. *Monmouthase* | ......... |
| 1............. | 1............. | 1............. | ............. | ............. | ......... |
| 2. Dellenose | 2. Vulsinose | 2............. | ............. | ............. | ......... |
| 3. Toscanose | 3. Pulaskose | 3. Procenose | ............. | ............. | ......... |
| 4. Lassenose | 4. Laurvikose | 4. Viezzenose | ............. | 4. Monmouthose | ......... |
| 5. Mariposose | 5. x | 5............. | ............. | ............. | ......... |
| 3. *Coloradase* | 3. x | 3............. | ............. | ............. | ......... |
| 1............. | 1............. | ............. | ............. | ............. | ......... |
| 2. x | 2. Mazarunose | ............. | ............. | ............. | ......... |
| 3. Amiatose | 3. x | ............. | ............. | ............. | ......... |
| 4. Yellowstonose | 4. x | ............. | ............. | ............. | ......... |
| 5. Amadorose | 5............. | ............. | ............. | ............. | ......... |
| 4. x | 4. *Labradorase* | 4. x | ............. | ............. | ......... |
| 1–2........... | 1–2........... | 1–2........... | ............. | ............. | ......... |
| 3............. | 3............. | 3............. | ............. | ............. | ......... |
| 4–5........... | 4–5. Labradorose | 4–5. x | ............. | ............. | ......... |
| ............. | 5. *Canadase* | ............. | ............. | ............. | ......... |

name has been suggested.

in Orders 3, 4, and 5. The following have received names in this system: Order 5, Indare; and Rang 5, Kyschtymase.

| ORDER | 1, $\frac{Q}{F} > \frac{7}{1}$ | 2, $\frac{Q}{F} < \frac{7}{1} > \frac{5}{3}$ | 3, $\frac{Q}{F} < \frac{5}{3} > \frac{3}{5}$ HISPANARE. |
|---|---|---|---|
| RANG 1, PERALKALIC, $\frac{K_2O + Na_2O}{CaO} > \frac{7}{1}$ | | | 1. *Varingase* |
| Subrang 1, Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$ | | | 1. |
| Subrang 2, Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$ | | | 2. |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | | | 3. Varingose |
| Subrang 4, Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$ | | | 4. x |
| Subrang 5, Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$ | | | 5. |
| RANG 2, DOMALKALIC, $\frac{K_2O + Na_2O}{CaO} < \frac{7}{1} > \frac{5}{3}$ | | | 2. x |
| Subrang 1. Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$ | | | 1. |
| Subrang 2, Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$ | | | 2. x |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | | | 3. x |
| Subrang 4, Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$ | | | 4. |
| Subrang 5, Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$ | | | 5. |
| RANG 3, ALKALICALCIC, $\frac{K_2O + Na_2O}{CaO} < \frac{5}{3} > \frac{3}{5}$ | | | 3. *Almerase* |
| Subrang 1, Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$ | | | 1. |
| Subrang 2, Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$ | | | 2. |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | | | 3. Almerose |
| Subrang 4, Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$ | | | 4. Sitkose |
| Subrang 5, Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$ | | | 5. |
| RANG 4, DOCALCIC, $\frac{K_2O + Na_2O}{CaO} < \frac{3}{5} > \frac{1}{7}$ | | | 4. x |
| Subrang 1–2, Prepotassic, $\frac{K_2O}{Na_2O} > \frac{5}{3}$ | | | 1–2. x |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$ | | | 3. |
| Subrang 4–5 Presodic, $\frac{K_2O}{Na_2O} < \frac{3}{5}$ | | | 4–5. x |
| RANG 5, PERCALCIC, $\frac{K_2O + Na_2O}{CaO} < \frac{1}{7}$ | | | 5. *Gordonase* |

NOTE. — X indicates that analyses are known which belong to this division, but that no name has been suggested.

| 4. $\frac{Q}{F} < \frac{3}{5} > \frac{1}{7}$ AUSTRARE. | 5. $\frac{Q, L}{F} < \frac{1}{7}$ GERMANARE. | 6. $\frac{L}{F} < \frac{3}{5} > \frac{1}{7}$ NORGARE. | 7. $\frac{L}{F} < \frac{5}{3} > \frac{3}{5}$ ITALARE. | 8. $\frac{L}{F} < \frac{7}{1} > \frac{5}{3}$ CAMPANARE. | 9. $\frac{L}{F} > \frac{7}{1}$ LAPPARE. |
|---|---|---|---|---|---|
| 1. *Pantellerase* | 1. *Umptekase* | 1. *Laurdalase* | 1. *Lujavrase* (*Chibinase*)[1] | 1. x | 1. *Urtase* |
| 1............ | 1............ | 1............ | 1............ | 1............ | 1............ |
| 2............ | 2. Highwoodose | 2. Fergusose | 2............ | 2............ | 2............ |
| 3. Grorudose | 3. Ilmenose | 3. Judithose | 3. Janeirose | 3. x | 3. Arkansose |
| 4. Pantellerose | 4. Umptekose | 4. Laurdalose | 4 Lujavrose (Chibinose)[1] | 4............ | 4. Urtose |
| 5............ | 5............ | 5............ | 5............ | 5. x | 5............ |
| 2. *Dacase* | 2. *Monzonase* | 2. *Essexase* | 2. *Vulturase* | 2. *Vesuvase* | ............ |
| 1............ | 1............ | 1............ | 1............ | 1............ | ............ |
| 2............ | 2. Ciminose | 2. Vicose | 2. Braccianose | 2 Vesuvose | ............ |
| 3. Adamellose | 3. Monzonose | 3. Borolanose | 3. x | 3............ | ............ |
| 4. Dacose | 4. Akerose | 4. Essexose | 4. Vulturose | 4. x | ............ |
| 5............ | 5. x | 5............ | 5............ | 5 ............ | ............ |
| 3. *Tonalase* | 3. *Andase* | 3. *Salemase* | 3. x | ............ | ............ |
| 1............ | 1............ | 1. x | 1............ | ............ | ............ |
| 2. x | 2. Auruncose | 2. x | 2............ | ............ | ............ |
| 3. Harzose | 3. Shoshonose | 3. x | 3. x | ............ | ............ |
| 4. Tonalose | 4. Andose | 4. Salemose | 4. x | ............ | ............ |
| 5. Placerose | 5. Beerbachose | 5. x | 5............ | ............ | ............ |
| 4. *Bandase* | 4. *Hessase* | 4. x | ............ | ............ | ............ |
| 1–2. Sagamose | 1–2............ | 1–2............ | ............ | ............ | ............ |
| 3. x | 3. x | 3............ | ............ | ............ | ............ |
| 4–5. Bandose | 4–5. Hessose | 4–5. x | ............ | ............ | ............ |
| ............ | 5. *Corsase* | ............ | ............ | ............ | ............ |

The $K_2O$, $Na_2O$ and CaO in these ratios are only those in the salic minerals.

[1] These names have been suggested by V. Hackman as more correctly derived.

| ORDER.............. | 1, $\frac{Q}{F} > \frac{7}{1}$ ........... | 2, $\frac{Q}{F} < \frac{7}{1} > \frac{5}{3}$ ........... | 3, $\frac{Q}{F} < \frac{5}{3} > \frac{3}{5}$ ATLANTARE. |
|---|---|---|---|
| RANG 1, PERALKALIC, $\frac{K_2O + Na_2O}{CaO} > \frac{7}{1}$..... | ........... | ........... | 1. *Rockallase* |
| Subrang 1, Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$...... | ........... | ........... | 1........... |
| Subrang 2, Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$... | ........... | ........... | 2........... |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$.. | ........... | ........... | 3. x |
| Subrang 4, Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$..... | ........... | ........... | 4........... |
| Subrang 5, Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$......... | ........... | ........... | 5. Rockallose |
| RANG 2, DOMALKALIC, $\frac{K_2O + Na_2O}{CaO} < \frac{7}{1} > \frac{5}{3}$ | ........... | ........... | ........... |
| Subrang 1, Perpotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1}$...... | ........... | ........... | ........... |
| Subrang 2, Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$... | ........... | ........... | ........... |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$.. | ........... | ........... | ........... |
| Subrang 4, Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$..... | ........... | ........... | ........... |
| Subrang 5, Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$......... | ........... | ........... | ........... |
| RANG 3, ALKALICALCIC, $\frac{K_2O + Na_2O}{CaO} < \frac{5}{3} > \frac{3}{5}$ | ........... | ........... | ........... |
| Subrang 1, Perpotassic, $\frac{K_2O}{Na_2O} > \frac{7}{1}$...... | ........... | ........... | ........... |
| Subrang 2, Dopotassic, $\frac{K_2O}{Na_2O} < \frac{7}{1} > \frac{5}{3}$... | ........... | ........... | ........... |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$.. | ........... | ........... | ........... |
| Subrang 4, Dosodic, $\frac{K_2O}{Na_2O} < \frac{3}{5} > \frac{1}{7}$..... | ........... | ........... | ........... |
| Subrang 5, Persodic, $\frac{K_2O}{Na_2O} < \frac{1}{7}$......... | ........... | ........... | ........... |
| RANG 4, DOCALCIC, $\frac{K_2O + Na_2O}{CaO} < \frac{3}{5} > \frac{1}{7}$... | ........... | ........... | ........... |
| Subrang 1–2, Prepotassic, $\frac{K_2O}{Na_2O} > \frac{5}{3}$..... | ........... | ........... | ........... |
| Subrang 3, Sodipotassic, $\frac{K_2O}{Na_2O} < \frac{5}{3} > \frac{3}{5}$.. | ........... | ........... | ........... |
| Subrang 4–5, Presodic, $\frac{K_2O}{Na_2O} < \frac{3}{5}$....... | ........... | ........... | ........... |
| RANG 5, PERCALCIC, $\frac{K_2O + Na_2O}{CaO} < \frac{1}{7}$...... | ........... | ........... | ........... |

NOTE. — X indicates that analyses are known which belong to this division, but that no name has been suggested.

| 4, $\frac{Q}{F} < \frac{3}{5} > \frac{1}{7}$ VAALARE. | 5, $\frac{Q, L}{F} < \frac{1}{7}$ GALLARE. | 6, $\frac{L}{F} < \frac{3}{5} > \frac{1}{7}$ PORTUGARE. | 7, $\frac{L}{F} < \frac{5}{3} > \frac{3}{5}$ KAMERUNARE. | 8, $\frac{L}{F} < \frac{7}{1} > \frac{5}{3}$ BOHEMARE. | 9, $\frac{L}{F} > \frac{7}{1}$ FINNARE. |
|---|---|---|---|---|---|
| 1........... | 1. *Orendase* | 1. *Wyomingase* | 1. *Malignase* | 1. *Chotase* | 1. *Ijolase* |
| ............ | 1. Orendose | 1. Wyomingose | 1.............. | 1............. | 1.......... |
| ............ | 2............. | 2............. | 2.............. | 2. Chotose | 2. Madupose |
| ............ | 3............. | 3. x | 3. x | 3............. | 3......... |
| ............ | 4. x | 4. x | 4. Malignose | 4............. | 4. Iiwarose |
| ............ | 5............. | 5............. | 5.............. | 5............. | 5. Ijolose |
| 2........... | 2. *Kilauase* | 2. *Monchiquase* | 2. *Kamerunase* | 2. *Albanase* | ........... |
| ............ | 1............. | 1............. | 1.............. | 1............. | ........... |
| ............ | 2. Prowersose | 2............. | 2. Jugose | 2. Albanose | ........... |
| ............ | 3. Lamarose | 3. Shonkinose | 3. Cascadose | 3. x | ........... |
| ............ | 4. Kilauose | 4. Monchiquose | 4. Kamerunose | 4. Covose | ........... |
| ............ | 5. x | 5............. | 5. x | 5. x | ........... |
| 3. *Vaalase* | 3. *Camptonase* | 3. *Limburgase* | 3. *Etindase* | .............. | ........... |
| 1........... | 1............. | 1............. | 1.............. | .............. | ........... |
| 2........... | 2. Absarokose | 2. Ottajanose | 2. Fiasconose | .............. | ........... |
| 3........... | 3. Kentallenose | 3. Ourose | 3.............. | .............. | ........... |
| 4. Vaalose | 4. Camptonose | 4. Limburgose | 4. Etindose | .............. | ........... |
| 5........... | 5. Ornose | 5. x | 5. x | .............. | ........... |
| 4. x | 4. *Auvergnase* | 4. x | 4. x | .............. | ........... |
| 1–2......... | 1–2........... | 1–2........... | 1–2............ | .............. | ........... |
| 3........... | 3. x | 3. x | 3. x | .............. | ........... |
| 4–5. x | 4–5. Auvergnose | 4–5. x | 4–5............ | .............. | ........... |
| ............ | 5. *Kedabekase* | .............. | ............... | .............. | ........... |

The $K_2O$, $Na_2O$ and CaO in these ratios are only those in the salic minerals.

## CLASS V, PERFEMANE, $\frac{SAL}{FEM} < \frac{1}{7}$. SUBCLASS I, PERFEMONE, $\frac{POM}{A} > \frac{7}{1}$.

| SECTION...... .. . | ORDER 1. $\frac{P,O}{R} > \frac{7}{1}$, MAORARE. | | | | |
|---|---|---|---|---|---|
| | 1, $\frac{P}{O} > \frac{7}{1}$ CAROLINIARE. | 2, $\frac{P}{O} < \frac{7}{1} > \frac{5}{3}$ MARYLANDIARE. | 3, $\frac{P}{O} < \frac{5}{3} > \frac{3}{5}$ | 4, $\frac{P}{O} < \frac{3}{5} > \frac{1}{7}$ GORDUNIARE | 5, $\frac{P}{O} < \frac{1}{7}$ MAORIARE. |
| RANG 1, PERMIRLIC, $\frac{CaO+MgO+FeO}{Na_2O} > \frac{7}{1}$ | 1. *Websterase* | 1. *Baltimorase* | 1...... ....... | 1. *Gordunase* | 1. *Dunase* |
| Section 1, Permiric, $\frac{MgO+FeO}{CaO} > \frac{7}{1}$.... | 1. Mariciase | 1. x | 1.............. | 1. Gorduniase | 1. Duniase |
| Subrang 1, Permagnesic, $\frac{MgO}{FeO} > \frac{7}{1}$ ... | 1. Maricose | 1. x | 1.............. | 1. Gordunose | 1. Dunose |
| Subrang 2, Domagnesic, $\frac{MgO}{FeO} < \frac{7}{1} > \frac{5}{3}$ | 2.............. | 2.............. | 2.............. | 2. x | 2.............. |
| Subrang 3, Magnesiferrous, $\frac{MgO}{FeO} < \frac{5}{3} > \frac{3}{5}$ | 3.............. | 3 .............. | 3.............. | 3.............. | 3.............. |
| Subrang 4, Doferrous, $\frac{MgO}{FeO} < \frac{3}{5} > \frac{1}{7}$.. | 4.............. | 4.............. | 4.............. | 4.............. | 4.............. |
| Subrang 5, Perferrous, $\frac{MgO}{FeO} < \frac{1}{7}$ ...... | 5.............. | 5.............. | 5 .............. | 5.............. | 5.............. |
| Section 2, Domiric $\frac{MgO+FeO}{CaO} < \frac{7}{1} > \frac{5}{3}$ | 2. Websteriase | 2. Baltimoriase | .............. | .............. | .............. |
| Subrang 1, Permagnesic, $\frac{MgO}{FeO} > \frac{7}{1}$..... | 1. Websterose | 1. x | .............. | .............. | .............. |
| Subrang 2. Domagnesic, $< \frac{7}{1} > \frac{5}{3}$.... | 2. Cecilose | 2. Baltimorose | Koswose | .............. | .............. |
| Subrangs 3. 4. and 5 not represented... | 3.............. | 3.............. | .............. | .............. | .............. |

Other orders of Class V are represented by analyses of iron ores, and in Order 2, Section 5, Rang 1, Section 1, Subrang 2, Permos, 1, Rhodase, Subrang 2, Rhodose. And in

| OI | ORDER 4, $\frac{P, O}{M} < \frac{3}{5} > \frac{1}{7}$, ADIRONDACKARE. | | | | | ORDER 5. |
|---|---|---|---|---|---|---|
| $\frac{P}{O}$ er Que | 1, $\frac{H}{T} > \frac{7}{1}$ ........ | 2, $\frac{H}{T} < \frac{7}{1} > \frac{5}{3}$ Adirondackore. | 3, $\frac{H}{T} < \frac{5}{3} > \frac{3}{5}$ Champlainore. | 4, $\frac{H}{T} < \frac{3}{5} > \frac{1}{7}$ x | 5, $\frac{H}{T} < \frac{1}{7}$ ........ | 2, $\frac{H}{T} < \frac{7}{1} > \frac{5}{3}$ ........ |
| *Qu* .. | ........ | 1. *Adirondackase* | 1. *Champlainase* | 1........ | ........ | 1........ |
| ...... | ........ | 1. Adirondackiase | 1. Champlainiase | 1........ | ........ | 1........ |
| ...... | ........ | 1.............. | 1.............. | 1........ | ........ | 1........ |
| ...... | ........ | 2.............. | 2.............. | 2........ | ........ | 2........ |
| ...... | ........ | 3.............. | 3.............. | 3........ | ........ | 3........ |
| ...... | ........ | 4. x | 4. x | 4........ | ........ | 4. x |
| ...... | ........ | 5.............. | 5.............. | 5........ | ........ | 5. x |
| . B .. | ........ | .............. | .............. | ........ | ........ | 2........ |
| . B .. | ........ | .............. | .............. | ........ | ........ | 1........ |
| . P .. | ........ | .............. | .............. | ........ | ........ | 2........ |
| ...... | ........ | .............. | .............. | ........ | ........ | 3........ |
| | | | | | | 4. x |
| ...... | ........ | .............. | .............. | ........ | ........ | ........ |
| ...... | ........ | .............. | .............. | ........ | ........ | ........ |
| ...... | ........ | .............. | .............. | ........ | ........ | ........ |
| ...... | ........ | .............. | .............. | ........ | ........ | ........ |

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Magmatic names carry with them an implication of the chemical composition and the standard mineral composition of the magmatic division to which they belong, there being quantitative limits to their application. To express the mode of a rock accurately the name must indicate the kinds of minerals actually present as well as their amounts. Owing to the wide range of possibilities in many cases this problem becomes exceedingly intricate and impracticable of exact solution. But an approximation may be made in the following manner:

If the mode is NORMATIVE, the chief minerals present in the rock are characteristic of the norm and are suggested by the magmatic name. To indicate this mode of the rock it is only necessary to use the word NORMATIVE with the magmatic name. When it is desirable to indicate what particular combination of feldspars is present, as when albite and anorthite unite, or orthoclase and some albite are in solid solution, this may be done by specifying the particular feldspars developed.

**Mineral Qualifiers.** — If there are minerals in the rock not characteristic of the norm, their presence may be indicated by using their special mineral names as qualifiers of the magmatic name. Two sets of cases may be distinguished by different methods: (1) When the distinctive minerals are present in such small amounts that they may be termed *varietal* minerals, that is, when they do not render the mode abnormative, the mineral name is given an adjective form by adding the suffix *-ic*, and the magmatic name is qualified by it; as *biotitic monzonose.* If it is desired to use the names of several varietal minerals, their names may be connected by hyphens and the last one modified by the suffix *-ic;* as *hornblende-biotitic monzonose.* (2) When the distinctive minerals are present in sufficient amounts to render the mode abnormative, that is, when they are *critical* minerals, their presence is indicated by uniting their mineral names with the magmatic name by means of hyphens; and when they are in different amounts the name of the most abundant is placed nearest to the magmatic name and the least abundant farthest from it: as *biotite-hornblende-andose.*

In naming a rock by this method the magmatic name employed may be of such a taxonomic value as represents the

degree of knowledge at hand respecting the composition of the rock. If it is only known to what Class it belongs, as of the second, it may be called simply a *dosalane*, or most likely a *dosalone*. If the relative proportions of the principal salic constitutents are known, the Order may be determined and it may be called a *norgare*, if of the sixth Order.

**Textural Qualifiers.** — The texture of a rock is indicated by an adjective expressing the fabric, the crystallinity, and the granularity, which may in some cases be abbreviated so as to be used as a prefix with the addition of the letter *o* to indicate that the texture is recognizable megascopically, and *i* to indicate that it is microscopic. For example:

*Grano* = megascopically granular; *grani* = microscopically granular.

*Grapho* = megascopically graphic; *graphi* = microscopically graphic.

*Vitro* = megascopically glassy; *vitri* = microscopically glassy.

Either the mineral or textural qualifiers may be placed next to the magmatic name according to the emphasis to be given them, it being understood that the term nearest the magmatic name carries the strongest emphasis.

**Type and Habit.** — It is obvious that if great precision is desired, and numerous mineral and textural qualifiers are to be used, the resulting polynomial name will be of considerable length, comparable with that which may be used in the qualitative system, as quartz-hornblende-biotite-diorite-porphyry. This may not be as great a difficulty as it at first appears, since, after a given rock has been described and named in full in any article, it may be referred to subsequently by its magmatic name, alone or with a textural or modal qualifier according to circumstances. When the same, or similar, assemblages of modal and textural characters are found in rocks at many localities it is desirable to express these concisely, that is, to designate a particular assemblage of characters by one denotive term. Two degrees of similarity may be recognized by different forms of suffixes applied to a denotive root word. One is almost complete *identity*, the other a *general resemblance.*

TYPE. — For the first, almost complete identity, may be used the term TYPE. Rocks may be said to be of the same type when

they are almost identical in *norm, mode,* and *texture.* They are so much alike that they may be mistaken for one another, or be parts of the same rock. For such a combination of modal and textural features a term is to be formed whose root is derived from the name of some geographical locality not already employed for a magmatic name and whose termination is to be *-al.*

HABIT. — When one rock resembles another in general appearance, by exhibiting some of its characteristic modal or textural features without being identical in composition or mode, they are said to possess the same HABIT. Thus two rocks may be porphyritic, having rhombic-shaped phenocrysts of feldspar in a dark-colored, aphanitic groundmass, but they may belong to different magmatic divisions, one having a notable amount of nephelite and the other not. To express the characteristic features of one in terms of the other, which may have been thoroughly described and named, a term is formed of a root, chosen as in the case of a typal term, with the termination *-oid.*

Thus a particular form of rock belonging to the lendofelic Order, russare, of the persalanes, may constitute a *tingual type,* with a definite norm, mode, and texture, while a somewhat similarly appearing rock belonging to the lendofelic Order, norgare, of the dosalanes, may possess a *tinguoid habit.* A habital qualifier may be applied to a magmatic name of any systematic division, since it does not specify the precise composition of a rock. Examples of the use of typal and habital terms in describing igneous rocks by this method are to be found in the study of the rocks of the Roman Region, Italy, by Washington.[1]

## METHOD OF CALCULATING THE NORM

Since the norms of rock magmas are standards by which they are to be compared with one another, and represent in each case one of a number of possible mineral compositions that may be assumed by a magma upon crystallizing, it is necessary to follow a definite method of calculation in establishing norms. The calculation is made from the statement of the chemical

[1] Washington, H. S. The Roman Comagmatic Region, Publication No. 57, Carnegie Institution of Washington, 1906.

composition of the rock, either as given in a chemical analysis obtained directly as such, or as estimated from an optical study of the mineral composition of the rock.

The method of procedure followed in the Quantitative System of Classification just described is based on certain chemico-mineralogical relations affecting the development and association of pyrogenetic minerals which have been discussed at some length in Chapter IV of Part I. They may be briefly summarized as follows:

SALIC MINERALS — There is a constant molecular ratio between the alkalies, potassium and sodium, and the alumina in the feldspars, in leucite and nephelite; and also between lime and alumina in anorthite. This ratio is 1 : 1.

The relative strength of chemical activity of these base-forming elements is such that potassium exerts a stronger hold on aluminium than does sodium, and both of these elements are more active in combining with it than is calcium. Consequently the demands of potassium are to be satisfied first so far as its combination with aluminium is concerned; then those of sodium, and lastly those of calcium.

If there is more alumina present than will satisfy the ratio of 1 : 1 with each of the elements named, the excess is calculated as corundum in the norm. If there is not sufficient alumina to satisfy the demands of potassium, sodium, and calcium, the elements are allotted to alumina in the order in which they are named.

The relative activities of these elements also determine their combination with silicic acids and the possible presence of quartz in the norm. Potassium and sodium will become polysilicates if there is sufficient silica when other demands on it are taken into account. And metasilicates and orthosilicates of these elements and aluminium will not form unless the silica is insufficient to form the polysilicates.

There is also a fixed ratio between zirconia and silica in zircon, namely, 1 : 1.

FEMIC MINERALS. — The only common femic mineral containing alkali is acmite, in which soda bears a constant ratio to ferric oxide, 1 : 1, and this compound does not form unless there is insufficient alumina to satisfy the alkalies in the magma.

There are a number of simple compounds with constant ratios between their components which may be expressed as follows: In magnetite, $FeO : Fe_2O_3 :: 1 : 1$. In ilmenite, $FeO : TiO_2 :: 1 : 1$. In titanite and perovskite, $CaO : TiO_2 :: 1 : 1$, the amount of silica in the magma determining whether the titanosilicate is developed or not. There is also a fixed ratio between lime and phosphorus pentoxide in apatite, $CaO : P_2O_5 :: 3.33 : 1$; and a constant ratio between lime and magnesia with ferrous oxide in diopside, $CaO : (Mg,Fe)O :: 1 : 1$.

The greater chemical activity of calcium than of magnesium and iron determines the higher silication of calcium when there is not sufficient silica to form metasilicates of all of these elements. And the absence of pyrogenetic wollastonite, $CaSiO_3$, together with the very common occurrence of diopside, $Ca(Mg,Fe)(SiO_3)_2$, determines the introduction of this compound among the femic normative minerals as the chief calcium-bearing femic mineral. The hold of calcium on magnesium and iron in this compound is so strong that they seldom form silicates independently of calcium, unless they are in excess of the calcium available for this or an analogous silicate. When there are not enough magnesium and iron for this purpose the excess of calcium must appear as a more calcic silicate, which in constructing a norm is calculated as wollastonite.

When there is an excess of magnesium and iron over that required in diopside it may form hypersthene or olivine, according to the amount of silica available after the more active base-forming elements are satisfied.

In rare instances sodium is so abundant in the magma that it enters ferromagnesian compounds without fixed ratios to other constituents, as in certain sodic amphiboles. This necessitates the introduction into the norm of simple sodium metasilicate, and still more rarely potassium metasilicate.

**Calculation of the Norm.** — The method of calculating the percentages of standard minerals in the norm of any igneous rock is as follows:

1. Determine the molecular proportions of the chemical components of a rock as expressed in its chemical analysis by dividing each percentage weight by the molecular weight of the particular component.

2. Small amounts of MnO and NiO are to be united with FeO; of BaO and SrO with CaO; and of $Cr_2O_3$ with $Fe_2O_3$, unless there is enough of any of these rare components to make it desirable to calculate their mineral molecules separately.

3. Those molecules that represent fixed or invariable compounds are established by making the following allotments:

(*a*) To $Cr_2O_3$, if present in notable amount, is allotted FeO in the ratio $Cr_2O_3$ : FeO : : 1 : 1, for chromite in the norm.

(*b*) To $TiO_2$ is allotted FeO in the ratio $TiO_2$ : FeO : : 1 : 1, for ilmenite. Excess of $TiO_2$ over available FeO is combined with CaO in the ratio CaO : $TiO_2$ : : 1 : 1, for perovskite or titanite according to the silica available, to be determined subsequently. Excess of $TiO_2$ after these allotments is to be calculated as rutile.

(*c*) To $P_2O_5$ is allotted CaO in the ratio $P_2O_5$ : CaO : : 1 : 3.33, for apatite. If fluorine is present in the analysis allot F to the lime in apatite in the ratio F : $P_2O_5$ : : 0.33 : 1.

(*d*) If there is fluorine in excess of that used for apatite allot to it CaO in the ratio Ca(O) : F : : 1 : 2, for fluorite.

(*e*) To Cl, if present, allot $Na_2O$ in the ratio Cl : $Na_2$(O) : : 2 : 1, for sodium chloride.

(*f*) To $SO_3$, if present, allot $Na_2O$ in the ratio $SO_3$ : $Na_2O$ : : 1: 1, for sodium sulphate.

(*g*) To S, if present, allot FeO in the ratio S : Fe(O) : : 2 : 1, for pyrite.

(*h*) To $CO_2$ in undecomposed rocks allot CaO in the ratio $CO_2$ : CaO : : 1 : 1, for calcite. If it is evident that there is secondary calcite in the rock, the $CO_2$ is not introduced into the norm but is neglected in the calculation.

The mineral molecules of more or less variable character generally form the major part of the norm and are calculated as follows:

4. To $K_2O$ is allotted $Al_2O_3$ in the ratio of 1 : 1, for orthoclase or leucite, according to the available silica which is to be determined subsequently. And to $Na_2O$, not already used in operations 3, (*e*), (*f*), is allotted $Al_2O_3$ in the ratio 1 : 1, for albite or nephelite, according to available silica afterwards determined.

5. If there is more $Al_2O_3$ than available $K_2O + Na_2O$,

(*a*) To excess of $Al_2O_3$ allot CaO in the ratio of 1:1, for anorthite.

(*b*) If there is still $Al_2O_3$ remaining it is to be calculated as corundum.

6. If there is less $Al_2O_3$ than available $K_2O + Na_2O$,

(*a*) It is first allotted to $K_2O$, and the remainder allotted to an equal number of molecules of $Na_2O$, the extra $Na_2O$ being combined with $Fe_2O_3$ in the ratio of 1 : 1, for acmite.

(*b*) If there is still excess of $Na_2O$ it is to be calculated as sodium metasilicate ($Na_2O \cdot SiO_2$).

(*c*) If, in an extremely rare instance, there is not enough $Al_2O_3$ to satisfy the $K_2O$, the excess of $K_2O$ is calculated as potassium metasilicate ($K_2O \cdot SiO_2$).

7. When the determination of both oxides of iron in the analysis is trustworthy the following allotments are made:

(*a*) To $Fe_2O_3$ is allotted $Na_2O$ under the condition 6, (*a*).

(*b*) To remaining $Fe_2O_3$ is allotted FeO in the ratio 1 : 1, for magnetite.

(*c*) If there is excess of $Fe_2O_3$ it is calculated as hematite.

When all the iron in the rock has been determined in the analysis in one form of oxidation, when it occurs in two and there is much iron present, no reliable norm can be calculated. But if the amount of iron is small the error in the calculation may be negligible. In such a case, if all the iron has been determined as ferric oxide, it is to be calculated as FeO, except that necessary for $Na_2O$ in acmite under condition 6, (*a*).

8. When there is CaO in excess of that already disposed of under conditions, 3 (*b*), (*c*), (*d*), and 5, (*a*), it is adjusted as follows:

(*a*) To the available CaO is allotted (Mg,Fe)O in the ratio of 1 : 1, for diopside, it being understood that in all cases where (Mg,Fe)O is used, MgO and FeO are taken in the same ratio to each other as that in which they are found in the analysis after FeO has been allotted to the molecules already mentioned. They are introduced into diopside, hypersthene, and olivine, with the same ratio between them in each case.

(*b*) If there is excess of CaO after providing for diopside it is set aside for calcium metasilicate ($CaSiO_3$), wollastonite, or sub-silicate ($4\ CaO \cdot 3\ SiO_2$), akermanite, according to available silica to be determined later.

9. When the available CaO is not sufficient to satisfy all the (Mg,Fe)O then the excess of (Mg,Fe)O is set aside for the metasilicate, hypersthene, or the orthosilicate, olivine, according to the available silica, which is determined as follows:

10. Silica is distributed among the several molecules, established by the adjustment of the base-forming components, by allotting $SiO_2$ first to those components that combine with it in only one ratio to form standard minerals.

(*a*) To $ZrO_2$ is allotted $SiO_2$ in the ratio of 1 : 1, for zircon.

(*b*) To CaO and $Al_2O_3$ in anorthite molecules is allotted $SiO_2$ in the ratio $CaO : SiO_2 :: 1 : 2$, to form $CaO \cdot Al_2O_3 \cdot 2\,SiO_2$.

(*c*) To CaO and MgO + FeO in diopside molecules is allotted $SiO_2$ in the ratio of $CaO + MgO + FeO : SiO_2 :: 1 : 1$, to form $CaO \cdot (Mg + Fe)O \cdot 2\,SiO_2$.

(*d*) To $Na_2O$ and $Fe_2O_3$ in acmite molecules is allotted $SiO_2$ in the ratio $Na_2O : SiO_2 :: 1 : 4$, to form $Na_2O \cdot Fe_2O_3 \cdot 4\,SiO_2$.

11. The allotment of $SiO_2$ to those components with which it may form more than one kind of silicate among the standard minerals is controlled by the relative chemical activities of the base-forming elements and the amount of silicon in the magma, as explained in Chapter IV of Part I. The alternate silicates are: the potassium compounds, orthoclase and leucite; sodium compounds, albite and nephelite; calcium compounds, wollastonite and akermanite; magnesium-iron compounds, hypersthene and olivine. In each case, when present, the lower silicate of the two must at least be formed. And since the alkalies are the more active elements and will form the higher silicates if possible, it will be the less active elements that will oftenest form the lower silicates of any pair. For these reasons the following method of adjusting $SiO_2$ has been adopted:

(*a*) In case there is evidently more than enough $SiO_2$ to form the higher silicates of each of these pairs of compounds, yielding an excess of $SiO_2$ to be calculated as quartz in the norm, the proper amount of $SiO_2$ is allotted in each case to form polysilicates of potassium and aluminium, $K_2O \cdot Al_2O_3 \cdot 6\,SiO_2$, and of sodium and aluminium, $Na_2O \cdot Al_2O_3 \cdot 6\,SiO_2$, as well as the metasilicates of calcium, $CaO \cdot SiO_2$, and of magnesium and iron, $(Mg,Fe)O \cdot SiO_2$. If there is any doubt as to the amount of $SiO_2$ being sufficient to make the higher silicates in all the cases

presented in a particular problem the method of procedure is as follows:

(*b*) To (Mg,Fe)O set aside for hypersthene or olivine allot sufficient $SiO_2$ to form olivine, that is, MgO + FeO : $SiO_2$ : : 2 : 1, forming 2 (Mg,Fe)O · $SiO_2$.

(*c*) To CaO set aside for wollastonite or akermanite allot sufficient $SiO_2$ to form wollastonite, that is, CaO : $SiO_2$ : : 1 : 1. This is because akermanite (melilite) is an extremely rare mineral, which only develops in magmas very low in silica.

(*d*) To $K_2O$ and $Na_2O$ with $Al_2O_3$ set aside for feldspars or lenads allot enough $SiO_2$ to form polysilicates in the ratio $K_2O$ + $Na_2O$ : $SiO_2$ : : 1 : 6, yielding $K_2O$ · $Al_2O_3$ · 6 $SiO_2$ and NaO · $Al_2O_3$ · 6 $SiO_2$.

(*e*) If there is excess of $SiO_2$ after these assignments, it is added to the orthosilicate of (Mg,Fe) to raise it to the metasilicate, that is, to convert 2 (Mg,Fe)O · $SiO_2$ to (Mg,Fe)O · $SiO_2$. If there is not enough $SiO_2$ to convert all of it to metasilicate it may be distributed by the following equations:

$$x + y = \text{molecules of MgO} + \text{FeO},$$
$$x + \frac{y}{2} = \text{available } SiO_2,$$

where $x$ = number of hypersthene molecules, $y$ = molecules of olivine.

(*f*) If there is excess of $SiO_2$ after operation 11, (*e*), it is allotted to the CaO · $TiO_2$ molecule set aside for titanite or perovskite. These constituents remain as perovskite if there is no excess of $SiO_2$ at this stage of the calculation.

(*g*) Further excess of $SiO_2$ is calculated as quartz in the norm.

12. If there is insufficient $SiO_2$ to form polysilicates of potassium and sodium under 11, (*d*), then the following adjustment is necessary:

(*a*) To $K_2O$ · $Al_2O_3$ is allotted enough $SiO_2$ to form polysilicate, $K_2O$ · $Al_2O_3$ · 6 $SiO_2$, and the remaining $SiO_2$ is distributed between albite and nephelite by means of the equations

$$x + y = \text{molecules of } Na_2O,$$
$$6\,x + 2\,y = \text{available } SiO_2,$$

where $x$ = number of albite molecules, $y$ = those of nephelite.

(*b*) If the $SiO_2$ is not sufficient to form nephelite out of all

the available $Na_2O$ under (*a*), then before allotting $SiO_2$ to the $K_2O$ molecules it is allotted to the $Na_2O$ so as to form nephelite, $Na_2O \cdot Al_2O_3 \cdot 2\ SiO_2$, and the remaining $SiO_2$ is distributed between orthoclase and leucite by means of the equations

$$x + y = \text{molecules of } K_2O,$$
$$6\,x + 4\,y = \text{available } SiO_2,$$

where $x$ = number of orthoclase molecules, $y$ = those of leucite.

13. If there is insufficient $SiO_2$ to form leucite and nephelite with olivine it is necessary to reduce a sufficient number of silicate molecules to lower forms to produce akermanite, $4\ CaO \cdot 3\ SiO_2$.

(*a*) In case there is no wollastonite, note the deficit of $SiO_2$ after leucite, nephelite, and olivine have been formed, and proceed to adjust the $SiO_2$ by the equation

molecules of akermanite ($4\ CaO \cdot 3\ SiO_2$) = $\frac{1}{3}$ the deficit of $SiO_2$.

That is, there will be $\frac{4}{3}$ as much CaO required to form akermanite as there is shortage in silica. This CaO is to be taken from the normative diopside, and the MgO and FeO so liberated are to be calculated as olivine, the $SiO_2$ thus released making up the deficit noted.

(*b*) In case there is wollastonite already formed this is first converted into akermanite by the equation just given.

(*c*) If there is not sufficient wollastonite to satisfy the deficit of silica, recalculate the molecules of diopside and wollastonite so as to make akermanite, olivine, and diopside by means of the formulæ

$$2\,x + 3\,y + \frac{z}{2} = \text{available } SiO_2,$$
$$x + 4\,y = \text{molecules of } CaO,$$
$$x + z = \text{molecules of } MgO + FeO,$$

where $x$ = molecules of new diopside, $y$ = molecules of akermanite, and $z$ = molecules of olivine.

14. If there is still a deficit of $SiO_2$ after all of the CaO has been allotted to akermanite, and all the (Mg,Fe)O has been reckoned as olivine, then the $K_2O$ must be distributed between leucite and kaliophilite by the equations

$$x + y = \text{molecules of } K_2O,$$
$$4\,x + 2\,y = \text{available } SiO_2,$$

where $x$ = number of leucite molecules, $y$ = those of kaliophilite.

15. In the extremely rare case in which there is still insufficient $SiO_2$, and an excess of $Al_2O_3$ and (Mg,Fe)O, which might form aluminous spinel, an alferic mineral, the excess of $Al_2O_3$ is to be calculated as corundum in the norm, and the uncombined (Mg,Fe)O is to be estimated as a femic mineral and placed with the nonsilicate, mitic group, which includes magnetite, ilmenite, etc.

As a result of this method of calculation certain standard minerals do not occur together in norms in this system.

Quartz does not appear in norms with leucite, nephelite, olivine, akermanite, or perovskite.

Hypersthene does not appear with leucite, nephelite, or akermanite.

Wollastonite does not appear with hypersthene or olivine.

Anorthite does not appear with acmite.

Albite does not appear with leucite.

Corundum does not appear with diopside or acmite.

**Percentage Weights of Minerals in the Norm.** — When the chemical components have been distributed in molecular proportion among the normative mineral compounds the percentage weights may be found by multiplying the number of molecules of each component in the several compounds by their molecular weights. This operation is greatly simplified by the use of tables both for finding the molecular proportions of the chemical components given in analyses[1] and for the percentage weights of the minerals whose molecular composition has been calculated. Such tables may be found in the publication of the Quantitative System noted below.[2]

**Examples of Calculations.** — The following examples of the method of calculating norms are taken from those given in the first publications of this system.[3] The first illustrates a case in which there is an excess of silica and one of alumina, yielding normative quartz and corundum. The femic silicate is hypersthene. The method of classifying the magma from the norm is

[1] Kemp, J. F. School of Mines Quarterly, vol. 22, pp. 75–88.

[2] Cross, Iddings, Pirsson, and Washington, The Quantitative System of Classification of Igneous Rocks, Chicago and London, 1903.

[3] *loc cit.*, pp. 652-659.

also shown. The second example illustrates the method of distributing $SiO_2$ between albite and nephelite after reckoning the femic silicate as olivine. The third case is one requiring the calculation of akermanite. After allotting $SiO_2$ to leucite, nephelite, anorthite, diopside, and olivine there is a deficit of 0.069 molecule of $SiO_2$. This example also illustrates the case of a magma intermediate between two Classes, II and III, and the resulting compound names.

## I.

### TOSCANOSE (GRANODIORITE) EL CAPITAN, YOSEMITE VALLEY, CAL.

*Bulletin* 168, *U. S. Geological Survey*, p. 208.

| | Per cent. | Mol. | Ilm. | Mag. | Orth. | Alb. | An. | Cor. | Hyp. | Quartz |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$... | 71.08 | 1.185 | .... | .... | 258 | 342 | 94 | .... | 27 | 464 |
| $Al_2O_3$.. | 15.90 | .156 | .... | .... | 43 | 57 | 47 | 9 | .... | .... |
| $Fe_2O_3$.. | .62 | .004 | .... | 4 | .... | .... | .... | .... | .... | .... |
| FeO... | 1.31 | .018 | 3 | 4 | .... | .... | .... | .... | 11 | .... |
| MgO... | .54 | .014 | .... | .... | .... | .... | .... | .... | 14 | .... |
| CaO... | 2.60 | .047 | .... | .... | .... | .... | 47 | .... | .... | .... |
| $Na_2O$.. | 3.54 | .057 | .... | .... | .... | 57 | .... | .... | .... | .... |
| $K_2O$... | 4.08 | .043 | .... | .... | 43 | .... | .... | .... | .... | .... |
| $H_2O$ + . | .30 | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| $H_2O$ − . | none | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| $CO_2$.... | tr | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| $TiO_2$... | .22 | .003 | 3 | .... | .... | .... | .... | .... | .... | .... |
| $P_2O_5$... | .10 | .000 | .... | .... | .... | .... | .... | .... | .... | .... |
| $SO_3$.... | none | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Cl..... | .02 | .000 | .... | .... | .... | .... | .... | .... | .... | .... |
| MnO... | .15 | .002 | .... | .... | .... | .... | .... | .... | 2 | .... |
| BaO... | .04 | .000 | .... | .... | .... | .... | .... | .... | .... | .... |
| SrO.... | .02 | .000 | .... | .... | .... | .... | .... | .... | .... | .... |
| $ZrO_2$... | .08 | .000 | .... | .... | .... | .... | .... | .... | .... | .... |
| | 100.60 | | | | | | | | | |

| FORMULA. | MOL. WT. | | NORM. | | | |
|---|---|---|---|---|---|---|
| $SiO_2$............... | 464 × 60 | = quartz | = 27.84 | Q | 27.84 | |
| $K_2O . Al_2O_3 . 6 SiO_2$... | 43 × 556 | = orthoclase | = 23.91 | | | |
| $Na_2O . Al_2O_3 . 6 SiO_2$.. | 57 × 524 | = albite | = 29.87 | F | 66.85 | Sal 95.61 |
| $CaO . Al_2O_3 . 2 SiO_2$... | 47 × 278 | = anorthite | = 13.07 | | | |
| $Al_2O_3$............. | 9 × 102 | = corundum | = .92 | C | .92 | |
| $MgO . SiO_2$.......... | 14 × 100 | = hypersthene | = 3.11 | P | 3.11 | |
| $(Fe,Mn)O . SiO_2$.... | 13 × 132 | | | | | Fem 4.49 |
| $FeO . Fe_2O_3$......... | 4 × 232 | = magnetite | = .93 | M | 1.38 | |
| $FeO . TiO_2$.......... | 3 × 152 | = ilmenite | = .45 | | | |
| | | | 100.10 | | | |

CLASS I. $\frac{Sal}{Fem} = \frac{95.6}{4.5} > \frac{7}{1}$, *Persalane.*

ORDER 4. $\frac{Q}{F} = \frac{27.8}{66.8} < \frac{3}{5} > \frac{1}{7}$, *Britannare.*

RANG 2. $\frac{K_2O' + Na_2O'}{CaO'} = \frac{100}{47} < \frac{7}{1} > \frac{5}{3}$, *Toscanase.*

SUBRANG 3. $\frac{K_2O'}{Na_2O'} = \frac{43}{57} < \frac{5}{3} > \frac{3}{5}$ *Toscanose.*

## II.

### NORDMARKOSE (LITCHFIELDITE), LITCHFIELD, ME.

*Bulletin* 168, *U. S. Geological Survey*, p. 21.

| | Per cent. | Mol. | Orth. | Alb. | Nep. | An. | Cor. | Mag. | Oliv. |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 612 | 68 | | | | |
| $SiO_2$ ....... | 60.39 | 1.006 | 300 | 680 | | 10 | ... | ... | 16 |
| | | | | 102 | 34 | | | | |
| $Al_2O_3$ ...... | 22.57 | .221 | 50 | 136 | | 5 | 30 | ... | ... |
| $Fe_2O_3$ ...... | .42 | .003 | .. | ... | .. | .. | .. | 3 | ... |
| $FeO$ ....... | 2.26 | .030 | .. | ... | .. | .. | .. | 3 | 27 |
| $MgO$ ....... | .13 | .003 | .. | ... | .. | .. | .. | .. | 3 |
| $CaO$ ....... | .32 | .005 | .. | ... | .. | 5 | .. | .. | .. |
| | | | | 102 | 34 | | | | |
| $Na_2O$ ...... | 8.44 | .136 | .. | 136 | | .. | .. | .. | .. |
| $K_2O$ ....... | 4.77 | .050 | 50 | ... | .. | .. | .. | .. | .. |
| $H_2O+$ / $H_2O-$ .... | .57 | ... | .. | ... | .. | .. | .. | .. | .. |
| $MnO$ ..... | .08 | .001 | .. | ... | .. | .. | .. | .. | 1 |
| | 99.95 | | | | | | | | |

$$1.006 - (0.300 + 0.010 + 0.016) = 0.680.$$
$$6x + 2y = 680\ (SiO_2).$$
$$x + y = 136\ (Na_2O).$$
$$x = 102.$$
$$y = 34.$$

In the rock the extra $Al_2O_3$ enters mica, combining with the olivine and magnetite molecules and because of low magnesia making lepidomelane.

| FORMULA. | MOL. WT. | NORM. | | | | |
|---|---|---|---|---|---|---|
| $K_2O \cdot Al_2O_3 \cdot 6\,SiO_2$ ..... | 50 × 556 | = orthoclase = | 27.80 | F | Sal | 95.35 |
| $Na_2O \cdot Al_2O_3 \cdot 6\,SiO_2$ .... | 102 × 524 | = albite = | 53.45 | | | |
| $CaO \cdot Al_2O_3 \cdot 2\,SiO_2$ ..... | 5 × 278 | = anorthite = | 1.39 | | | |
| $Na_2O \cdot Al_2O_3 \cdot 2\,SiO_2$ .... | 34 × 284 | = nephelite = | 9.66 | L | | |
| $Al_2O_3$ ............... | 30 × 102 | = corundum = | 3.06 | C | | |
| $FeO \cdot Fe_2O_3$ .......... | 3 × 232 | = magnetite = | .70 | M | Fem | 3.81 |
| $2\,MgO \cdot SiO_2$ .......... | 3 × 70 | = olivine = | 3.11 | O | | |
| $2\,FeO \cdot SiO_2$ .......... | 28 × 102 | | | | | |
| | | $H_2O$ = | .57 | | | |
| | | | 99.73 | | | |

CLASS 1. $\frac{Sal}{Fem} = \frac{95.35}{3.81} > \frac{7}{1}$, *Persalane.*

ORDER 5. $\frac{L}{F} = \frac{9.66}{82.64} < \frac{1}{7}$, *Canadare.*

RANG 1. $\frac{K_2O' + Na_2O'}{CaO'} = \frac{186}{3} > \frac{7}{1}$, *Nordmarkase.*

SUBRANG 4. $\frac{K_2O'}{Na_2O'} = \frac{50}{136} < \frac{3}{5} > \frac{1}{7}$ *Nordmarkose.*

## III.

## VESUVOSE-ALBANOSE (LEUCITE). CAPO DI BOVE, ITALY.

*American Journal Science*, Vol. 9 (1900), p. 56.

| | Per cent. | Mol. | Ilm. | Leuc | Nep. | An. | Mag. | Tentative. Diop. | Tentative. Oliv. | Deficit. | Final. Ak.[1] | Final. Diop | Final. Oliv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$... | 45.99 | .767 | .. | 376 | 70 | 78 | .. | 298 | 14 | 69 | 69 | 114 | 60 |
| $Al_2O_3$.. | 17.12 | .168 | .. | 94 | 35 | 39 | .. | ... | .. | .. | .. | ... | .. |
| $Fe_2O_3$.. | 4.17 | .026 | .. | .. | .. | .. | 26 | ... | .. | .. | .. | ... | .. |
| FeO... | 5.38 | .075 | 5 | .. | .. | .. | 26 | 37 | 7 | .. | .. | 14 | 30 |
| MgO... | 5.30 | .133 | .. | .. | .. | .. | .. | 112 | 21 | .. | .. | 43 | 90 |
| CaO... | 10.47 | .187 | .. | .. | .. | 39 | .. | 148 | .. | .. | 92 | 56 | .. |
| $Na_2O$.. | 2.18 | .035 | .. | .. | 35 | .. | .. | ... | .. | .. | .. | .. | .. |
| $K_2O$... | 8.97 | .094 | .. | 94 | .. | .. | .. | ... | .. | .. | .. | .. | .. |
| $H_2O$... | .45 | .... | .. | .. | .. | .. | .. | ... | .. | .. | .. | .. | .. |
| $TiO_2$... | .37 | .005 | 5 | .. | .. | .. | .. | ... | .. | .. | .. | .. | .. |
| MnO... | tr | .... | .. | .. | .. | .. | .. | ... | .. | .. | .. | .. | .. |
| BaO... | .25 | .001 | .. | .. | .. | .. | .. | 1 | .. | .. | .. | 1 | .. |
| SrO.... | none | .... | .. | .. | .. | .. | .. | ... | .. | .. | .. | .. | .. |
| | 100.65 | | | | | | | | | | | | |

[1] Mol. of akermanite $= y = \frac{69}{3} = 23$.

| FORMULA. | MOL. WT. | | NORM. | | |
|---|---|---|---|---|---|
| $K_2O . Al_2O_3 . 4 SiO_2$..94 | × 436 | = leucite | = 40.98 | L = 50.92 | Sal 61.76 |
| $Na_2O . Al_2O_3 2 SiO_2$..35 | × 284 | = nephelite | = 9.94 | | |
| $CaO . Al_2O_3 . 2 SiO_2$..39 | × 278 | = anorthite | = 10.84 | F = 10.84 | |
| $CaO . SiO_2$.........57 | × 116 | = diopside | = 12.76 | P = 12.76 | Fem 38.20 |
| $MgO . SiO_2$.........43 | × 100 | | | | |
| $FeO . SiO_2$.........14 | × 132 | | | | |
| $2 MgO . SiO_2$.......90 | × 70 | = olivine | = 9.36 | O = 18.65 | |
| $2 FeO . SiO_2$.......30 | × 102 | | | | |
| $4 CaO . 3SiO_2$......23 | × 404 | = akermanite | = 9.29 | | |
| $FeO . Fe_2O_3$........26 | × 232 | = magnetite | = 6.03 | M = 6.79 | |
| $FeO . TiO_2$......... 5 | × 152 | = ilmenite | = .76 | | |
| | | $H_2O$ | = .45 | | |
| | | | 100.41 | | |

CLASS III. ORDER 8. RANG 2. SUBRANG 2.

$$\frac{Sal}{Fem} = \frac{61.76}{38.20} < \frac{5}{3} > \frac{3}{5},\ \frac{L}{F} = \frac{50.92}{10.84} < \frac{7}{1} > \frac{3}{5},\ \frac{K_2O' + Na_2O'}{CaO'} = \frac{129}{39} < \frac{7}{1} > \frac{5}{3},\ \frac{K_2O'}{Na_2O'} = \frac{94}{35} < \frac{7}{1} > \frac{5}{3}$$

*Dosalane-salfemane.* *Campanare-bohemare.* *Vesuvase-albanase.* *Vesuvose-albanose.*

**Calculation of Norm from Mode.** — When the mode of a rock, its actual mineral composition, can be determined quantitatively with reasonable accuracy, and the chemical composition of the constituent minerals is also determinable or can be approximated closely, it is possible to calculate the chemical composition of the rock as a whole and from this analysis reckon the normative minerals by the method just described. This process of obtaining the norm of a rock is only applicable to holocrystalline rocks whose mineral composition is recognizable and determinable optically. It cannot be applied to glassy rocks, or to holocrystalline ones whose crystals are too minute to be identified or measured.

When all the minerals are recognizable and measurable their relative amounts in volume may be determined by measuring with a micrometer the distance across each crystal in lines through thin sections of a rock, when the fabric is such that the lines along which the measurements are made yield average diameters for all kinds of crystals. The method cannot be employed with safety when the texture is laminated, if there are different kinds of minerals. In order that the error of measurement may be as small as one per cent in any case, it is necessary to measure a distance across the rock at least one hundred times its average grain.

The proportions found for the lengths of the sections across the various crystals will correspond to their relative volumes.[1] From these the relative masses or percentage weights are derived by multiplying each volume by the specific gravity of the corresponding mineral and reducing the total to one hundred parts.

Coarse-grained rocks and those with large phenocrysts must be measured megascopically on the surface of proper-sized specimens. In the case of porphyritic rocks the relative proportions of phenocrysts and groundmass must be determined megascopically and the composition of the groundmass determined microscopically. In extremely fine-grained rocks when some of the constituents are colorless and others colored, the amount of the former is apt to be underestimated because the colored crystals show through them when they wedge over one another.

[1] Rosiwal, Verh. Wien. Geol. Reichs-Anst., vol. 32, 1898, p. 143.

When the percentage weights of the component minerals have been determined the chemical constituents in the rock are found by multiplying the percentages of the chemical components in each kind of mineral by the percentage of the mineral in the rock. In a few minerals the chemical composition is definite and may be derived from the formula of the mineral or from other sources.

The chemical composition of the feldspars is determinable by optical means, from the refraction or optical orientation of the crystals as described in text-books of the rock minerals. It is to be noted that the ratios between albite and anorthite expressed by Ab : An deal with the molecules $NaAlSi_3O_8$ = Ab and $CaAl_2Si_2O_8$ = An, whereas the molecules derived by the method of calculating the normative minerals are $Na_2Al_2(Si_3O_8)_2$ = albite and $CaAl_2(SiO_4)_2$ = anorthite. That is, the normative albite molecule is twice as large as that represented by Ab, while the anorthite molecules are the same in both cases. This is a source of confusion in the calculation of the lime-soda-feldspars from chemical analyses where the units of comparison are $Na_2O$ and CaO and not Na and Ca. Owing to the similarity in the molecular weights of the Ab and An molecules, 262 and 278, it is sufficiently accurate in most cases where the ratio between these molecules has been determined optically on zonally built feldspars to apply this ratio Ab/An directly to the estimation of the percentage weights of albite and anorthite from that of the total plagioclase measured. Thus 50 per cent of plagioclase with the average composition $Ab_3An_2$ consists approximately of 30 per cent albite and 20 per cent anorthite.

For other minerals with variable composition such as the amphiboles, pyroxenes, and micas, the relation between the optical properties and the chemical composition is not definitely known at present. But the color and other optical properties may be used in a general way as guides to the choice of typical formulæ or special chemical analyses. Moreover it appears that the amphiboles in similar rocks usually have similar compositions, so that it is possible to select from a collection of analyses of different amphiboles one that will correspond closely to the composition of a particular amphibole in a new rock under

investigation. The same is true of most pyroxenes and micas. Furthermore, when the percentages of these minerals in a rock are small, errors due to inaccuracies in specific analyses are often negligible. In order to supply such a collection of analyses for amphiboles, pyroxenes, and micas, those cited in the first publication of the Quantitative System are repeated in the accompanying tables. When there are any of these minerals in the mode it is necessary to select an analysis from one of those given in the table which corresponds most closely to what is to be expected for the mineral in the mode, considering its optical properties and the general character of the rocks to which each belongs. The constituents in the analysis are then reduced in proportion to the percentage of the mineral in the mode and added to the other chemical constituents of the rock derived from the mode. Having assembled all the chemical constituents in this way the chemical composition of the rock as a whole is obtained. From this the norm may be calculated in the manner already described.

MODES OF THE "BUTTE GRANITE"

| | First Rock. | | | | Second Rock. | |
|---|---|---|---|---|---|---|
| | Total Diameters. | Relative Volumes. | Sp. gr. | Weights. | Relative Volumes. | Weights. |
| Quartz........ | 2,954 | 23.17 | 2.65 | 22.55 | 20.97 | 20.34 |
| Orthoclase..... | 2,373 | 18.62 | 2.57 | 17.57 | 21.07 | 19.82 |
| Plagioclase.... | 5,492 | 43.10 | 2.68 | 42.47 | 42.29 | 41.48 |
| Biotite........ | 1,130 | 8.87 | 3.00 | 9.77 | 8.15 | 8.94 |
| Hornblende.... | 482 | 3.78 | 3.20 | 4.44 | 4.84 | 5.67 |
| Pyroxene...... | 252 | 1.97 | 3.30 | 2.37 | 2.07 | 2.50 |
| Magnetite..... | 51 | .40 | 5.17 | .76 | .54 | 1.02 |
| Pyrite......... | 6 | .04 | 5.00 | .07 | .02 | .04 |
| | 12,740 | 99.95 | | 99.98 | 99.95 | 99.81 |

**Calculation of Chemical Analysis from Mode.** — The following example of the calculation of analyses from the mode of a rock will illustrate the method. The rock examined was a medium-grained phanerocrystalline rock from Butte, Mont., the Butte granite. Sections from two localities were measured micro-

scopically by the Rosiwal method. In the first section an aggregate distance of 12,470 units of the micrometer scale was measured, in the second section a distance of 7122 units. In the first case 604 measurements were made, in the second 403. In the first case the average section across the plagioclase crystals was 32 units and the total distance through plagioclase was 5492 units. In the second case these quantities were 24 and 3012. The minerals composing the rock, and their relative volumes and percentage weights are shown in the table on page 447.

CHEMICAL COMPOSITION OF THE "BUTTE GRANITE" CALCULATED FROM ITS MODE

| | Biotite. | Hornblende and pyroxene. | Magnetite. | Pyrite. | Anorthite. | Albite. | Orthoclase. | Quartz. | First Rock. | Second Rock. | Atlantic Mine. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 3.58 | 3.11 | | | 7.66 | 16.97 | 11.37 | 22.55 | 65.24 | 64.43 | 64.34 |
| $Al_2O_3$ | 1.37 | .46 | | | 6.52 | 4.81 | 3.22 | | 16.38 | 16.46 | 15.72 |
| $Fe_2O_3$ | .52 | .34 | .52 | | | | | | 1.38 | 1.57 | 1.62 |
| $FeO$ | 1.37 | .71 | .23 | .04 | | | | | 2.35 | 2.42 | 2.94 |
| $MgO$ | 1.21 | .82 | | | | | | | 1.93 | 2.10 | 2.17 |
| $CaO$ | .00 | .76 | | | 3.57 | | | | 4.33 | 4.38 | 4.24 |
| $Na_2O$ | .01 | .05 | | | | 2.93 | | | 2.99 | 2.95 | 2.76 |
| $K_2O$ | .91 | .08 | | | | | 2.97 | | 3.96 | 4.27 | 4.04 |
| $H_2O-$ | .12 | .03 | | | | | | | .15 | .15 | .25 |
| $H_2O+$ | .36 | .16 | | | | | | | .52 | .43 | .76 |
| $TiO_2$ | .35 | .10 | | | | | | | .45 | .35 | .53 |
| $P_2O_5$ | .01 | .02 | | | | | | | .03 | .04 | .14 |
| $MnO$ | .02 | .04 | | | | | | | .06 | .06 | .12 |
| $SrO$ | | | | | | | | | | | .03 |
| $BaO$ | .01 | | | | | | | | .01 | .01 | .06 |
| $Cl$ | .02 | | | | | | | | .02 | .02 | .03[1] |
| $F$ | .07 | .02 | | | | | | | .09 | .09 | .005[2] |
| $S$ | | | | .04 | | | | | .04 | .02 | .03[3] |
| | | | | | | | | | | | .02[4] |
| | | | | | | | | | 99.93 | 99.75 | 99.805 |

[1] $CO_2$. [2] Cu. [3] $FeS_2$. [4] $ZrO_2$.

The plagioclase is zonally built and an optical study places the average composition at about $Ab_3An_2$, furnishing by molecular calculation 24.71 Ab, 17.76 An for the first rock, and 24.29 Ab, 17.18 An for the second. The hornblende and pyrox-

ene together have been analyzed as "pure" hornblende, whose analysis is given in the table of amphibole analyses (anal. *b*), and the mica also from this rock has been analyzed and is given in the table of mica analyses (anal. *c*). The chemical constituents derived from these sources are placed in the table on page 448 and the resulting estimated analyses of the two specimens of Butte granite studied optically are given in the columns headed First and Second Rock. The chemical analysis of a third specimen of Butte granite taken from the Atlantic mine and analyzed by chemical methods[1] is cited for comparison. The success of the optical method in this instance is apparent.

## CHEMICAL CLASSIFICATION OF THE QUALITATIVE SYSTEM

**Osann's Chemical Classification.**[2] — Dr. A. Osann has undertaken to express the mineralogical classification of Rosenbusch in terms of the chemical composition of the rocks, preserving the groups and definitions of that system and setting up within each of the larger Families a series of chemical types. There is no attempt to readjust the boundaries between the principal groups of rocks or to suggest a new nomenclature.

The method followed by Osann is to select analyses of unaltered rocks so far as possible and reduce the percentage weights to molecular proportions after the analyses have been recalculated to a summation of 100. $TiO_2$, $ZrO_2$, and $P_2O_5$ are reckoned with $SiO_2$; BaO and SrO are united with CaO. $Fe_2O_3$ is reduced to FeO, except in cases where $Fe_2O_3$ is needed to combine with excess of $Na_2O$ to form acmite molecules when $K_2O + Na_2O > Al_2O_3$.

The molecular proportions thus obtained are arranged in several groups which constitute the coördinates by means of which the chemical types are compared. The grouping is as follows:

1. The percentage weight of $SiO_2$ together with that of $ZrO_2$ forms one factor, designated by *s*.

[1] Stokes, H. N., analyst, U. S. Geological Survey, Bulletin 168, 1900, p. 117.

[2] Osann, A. Versuch einer Chemischen Classification der Erupstivgesteine. Tscher. min. petr. Mitth., vol. 19, 1900, pp. 351–469; and vol. 20, 1901, pp. 399–558; vol. 21, 1902, pp. 365–448; vol. 22, 1903, pp. 322–436.

2. The alkalies and alumina are united molecularly into a group $(K,Na)_2Al_2O_4$; and the alkalies so used are designated by $A$, that is, $A = K_2O + Na_2O$.

3. Alumina remaining after operation 2 is combined with lime to form a group $CaAl_2O_4$; and the lime so used is designated by $C$.

4. The remaining CaO is united with FeO, MnO, MgO, SrO, and BaO into a group designated by $F$.

5. The sum of the alkalies, $K_2O + Na_2O$, is recalculated so as to equal 10, and the value of $Na_2O$ so obtained is designated by $n$.

The coördinating factors are $s$, $A$, $C$, $F$, and $n$. Of these, $A$, $C$, and $F$ are used to plot the position of the analysis of a rock in an equilateral triangle, and in each case they are recalculated so that their sum may equal 20, their recalculated values being designated by the letters $a$, $c$, and $f$. The corners of the triangle are lettered $A$, $C$, $F$, at which points each of the factors $a$, $c$, $f$ becomes a maximum respectively, that is, 20. The whole rock may be expressed by a formula composed of the factors, $s$, $a$, $c$, $f$, $n$. For a complete exposition of the system and the resulting types suggested by Osann the student is referred to the publications already cited.

## MEGASCOPICAL PETROGRAPHY

Owing to the intricate nature of the inherent qualities and relationships of rocks, which involve chemical and mineral factors that require special knowledge for their recognition and treatment, and because of the rapid advancement of petrology along the lines of chemical and physical, including optical, research, the petrography of igneous rocks has passed beyond the reach of many whose acquaintance with rocks must of necessity be partial, but who, nevertheless, require a certain amount of knowledge of rocks, and the means of describing them to the extent of such knowledge. This applies to many geologists, mining engineers, and other workers in geological fields. It applies in a measure to petrologists themselves, for many of the characteristics of rocks are not discernible except upon chemical or microscopical investigation, which can only be undertaken in the laboratory, so that the preliminary diagnosis of

some rocks which must be relied upon in field work must rest upon those features which are recognizable megascopically. Thus the specific characters of the feldspars even when megascopic and the composition of aphanitic rocks cannot be determined offhand.

For these reasons there is need of some systematic treatment of rocks which can be followed by those not prepared to pursue the more specialized methods of determination and description. Such a treatment should be based on qualities readily recognized without the use of a microscope, and the names used in describing the rocks should be defined wholly in terms of such megascopic characters. Their application should be purely objective, and should not involve conceptions of what might be in the rock because of its resemblance to others that have been studied microscopically and chemically, for such resemblances are sometimes misleading. The names of rocks defined on purely megascopic data must have quite different applications from those defined in terms of microscopical and chemical characters. Consequently rock names should not be the same in two systems that are fundamentally different.

Many names given to rocks by the earlier geologists were originally defined in terms of megascopic characters, and are equally appropriate at the present day to rocks having such qualities. With slight modification in some instances, in order that they may accord with a somewhat more systematic treatment of the nomenclature, they may be employed for a system of megascopical petrography which will be useful in all field work, and will be of permanent value to those who do not require the more precise definitions of advanced petrology.

Such a megascopic petrography of igneous rocks has been outlined in the first publication of the Quantitative System of Classification of Igneous Rocks,[1] and has been successfully elaborated by Pirsson in his book entitled "Rocks and Rock Minerals,"[2] in which rocks are described and treated on a purely

[1] Cross. Iddings, Pirsson, and Washington, Jour. Geol., vol. 10, 1902; and Quantitative Classification of Igneous Rocks, Chicago and London, 1903, pp. 180–185

[2] Pirsson, L. V. Rocks and Rock Minerals, New York and London, 1908.

megascopical basis. The system of classification proposed for what may be called megascopic petrography is briefly as follows:

All igneous rocks are divided according to texture into three divisions or classes:

I. PHANERITES, or GRAINED ROCKS (Pirsson). — All rocks whose component minerals are large enough to be seen by the unaided eye.

II. APHANITES, or DENSE ROCKS (Pirsson). — Aphanitic or lithoidal rocks, whose component crystals are so minute that they cannot be seen and recognized by the unaided eye. This applies to the groundmass of porphyritic rocks, whose phenocrysts may be recognizable megascopically

III. GLASSY ROCKS. — Those that are in part or wholly composed of glass, which may be recognizable by the unaided eye.

Rocks of Division I are subdivided according to mineral composition into two groups: (*a*) those in which feldspar or quartz, or both together predominate; (*b*) those in which ferromagnesian minerals predominate. These are further subdivided into two groups as follows:

(*a*) 1. *Rocks with preponderant quartz and feldspars.*

GRANITE. — All granular igneous rocks composed of dominant quartz and feldspar of any kind, with subordinate ferromagnesian minerals of any kind, mica, hornblende, or pyroxene. This is the granite of Werner, von Leonhard, and others, and includes rocks now called granite, granodiorite, most quartz-diorites, and other light-colored quartzose rocks rich in feldspar. When porphyritic and fine-grained it is GRANITE-PORPHYRY.

(*a*) 2. *Rocks with preponderant feldspars, with little or no quartz.*

SYENITE. — All granular igneous rocks composed of dominant feldspar of any kind, with subordinate amounts of ferromagnesian minerals, and without noticeable amount of quartz. This includes modern syenite, anorthosite, and the more feldspathic monzonites, diorites, and gabbros.

(*b*) 1. *Rocks with preponderant ferromagnesian minerals and smaller amounts of feldspar.*

DIORITE. — When the ferromagnesian mineral is hornblende for the most part. This is the diorite of d'Aubuisson, as defined

by von Leonhard, and includes the less feldspathic of modern diorites and hornblende-gabbros.

GABBRO. — Those with dominant pyroxene, essentially the gabbro of von Leonhard. In those cases in which the ferromagnesian mineral does not appear to be hornblende it will be safe to consider it pyroxene and call the rock gabbro.

(*b*) 2. *Rocks composed almost wholly of ferromagnesian minerals.*
PERIDOTITE. — When there is considerable olivine present.
PYROXENITE. — When the rock is almost wholly pyroxene.
HORNBLENDITE. — When it is almost wholly hornblende.

Other names for rocks of any of these divisions may be used according to the definitions in the Qualitative Mineralogical System when the constituent minerals are recognizable megascopically.

Rocks of Division II are divided according to whether they are (*a*) *non-porphyritic*, or (*b*) *porphyritic*, and according to whether they are *light-colored* or *dark-colored.*

(*a*) 1. FELSITE. — All light-colored aphanitic rocks that have no appreciable amount of phenocrysts. They may be of various tones of color and of various compositions.

(*a*) 2. BASALT. — All dark-colored aphanitic rocks without appreciable amounts of phenocrysts.

(*b*) Porphyritic rocks with aphanitic groundmass are called PORPHYRIES whatever their composition. When divided according to light and dark color they become

(*b*) 1. LEUCOPHYRE. — A term first used by Gümbel for certain light-colored porphyries. They may also be called FELSITE-PORPHYRY.

(*b*) 2. MELAPHYRE. — A name used by Brongniart; dark-colored porphyries, which may also be called BASALT-PORPHYRY.

When the phenocrysts are recognizable, porphyries may be further named according to the kinds of phenocrysts, as QUARTZ-PORPHYRY or QUARTZ-FELSITE-PORPHYRY, AUGITE-BASALT-PORPHYRY, and so on.

Rocks of Division III are grouped according to the character of the glassy portion of the rock as

OBSIDIAN. — Vitreous rocks of any color, usually black, often red, less often brown or greenish.

PITCHSTONE. — Resinous, less lustrous than obsidian and generally lighter colored.

PERLITE. — Glassy rocks with perlitic structure, usually gray in color.

PUMICE. — Highly vesicular glass, usually very light-colored.

When glassy rocks are notably porphyritic they may be called VITROPHYRE, and may be qualified by the name of the prominent phenocrysts, as QUARTZ-VITROPHYRE, FELDSPAR-VITROPHYRE and MICA-FELDSPAR-VITROPHYRE.

| | | o | p | |
|---|---|---|---|---|
| Hor | Cossyrite. | Ainigmatite. | Rock. | Amphibole. |
| 45. | 43.55 | 37.92 | 74.76 | 49.10 |
| | .726 | .632 | | .818 |
| 6. | 4.96 | 3.23 | 11.60 | 5.50 |
| | .048 | .031 | | .054 |
| 4. | 7.97 | 5.81 | 3.50 | 4.20 |
| | .049 | .036 | | |
| 10. | 32.87 | 35.88 | .19 | 27.70 |
| | .456 | .498 | | .385 |
| 12. | .86 | .33 | .18 | .17 |
| | .021 | .008 | | .004 |
| 11. | 2.01 | 1.36 | .07 | .13 |
| | .036 | .024 | | .002 |
| | 5.29 | 6.58 | 4.35 | 10.50 |
| | .085 | .106 | | .169 |
| 1. | .33 | .51 | 4.92 | 1.60 |
| | .003 | .005 | | .017 |
| 2. | ... | .... | .64 | .... |
| | ... | .... | .... | .... |
| 1. | ... | 7.57 | trace | .... |
| | | .094 | | |
| | ... | .... | trace | .... |
| | ... | .... | .... | .... |
| | ... | .... | .... | .... |
| | ... | .... | .... | .... |
| | 1.98 | .100 | .... | .50 |
| | .027 | .013 | | .007 |
| no | ... | .... | .... | .... |
| no | CuO .39 | .... | .... | .... |
| F. | 100.21 | 100.19 | 100.21 | 99.40 |
| 98. | 3.74 | 3.80 | .... | .... |
| | 3.75 | 3.852 | .... | .... |
| 98. | | | | |

Mt. *...te-syenite*, Kangerdluarsuk, Greenland,
...anose ...n *pantellerite* (felso-varingose), Kharti-
...ion). ... *El. Gest.*, p. 257.
... p. 2... *syenite*, Julianehaab, Greenland, Rosen-
...amia...
...v., p. ... (felso-liparose), San Pietro, Sardinia,
...a, ro...
...el Cal...

## OF MICAS AND OF THE ROCK

| | c | d | | e | | |
|---|---|---|---|---|---|---|
| . | Mica. | Rock. | Mica. | Rock. | Mica. | Rock. |
| 8 | 35.79 | 66.91 | 35.62 | 77.61 | 31.96 | 60.39 |
| | .596 | | .594 | | .533 | |
| 4 | 13.70 | .... | 15.24 | 11.94 | 11.93 | 22.57 |
| | .134 | | .149 | | .117 | |
| 1 | 5.22 | .... | 4.69 | .55 | 8.06 | .42 |
| | .032 | | .029 | | .050 | |
| 9 | 13.72 | .... | 13.67 | .87 | 30.35 | 2.26 |
| | .190 | | .190 | | .421 | |
| 3 | 12.13 | .... | 12.70 | trace | .05 | .1 |
| | .303 | | .317 | | .001 | |
| 7 | .05 | 3.51 | .95 | .31 | .23 | .3 |
| | .001 | | .017 | | .004 | |
| 1 | .15 | 3.59 | .50 | 3.80 | 1.54 | 8.4 |
| | .002 | | .008 | | .025 | |
| 3 | 9.09 | 3.18 | 7.72 | 4.98 | 8.46 | 4.7 |
| | .097 | | .082 | | .090 | |
| 6 | 3.64 | .... | 4.36 | trace | 4.25 | .5 |
| | | | .242 | | | |
| 2 | 1.21 | .... | .94 | .23 | ... | ... |
| . | ... | .... | ... | .... | ... | ... |
| 5 | 3.51 | ... | 2.61 | .25 | 3.42 | ... |
| | .044 | | .033 | .... | .043 | |
| 1 | .10 | .... | none | .... | ... | ... |
| 4 | ... | .... | ... | .... | ... | ... |
| ? | .20 | .... | ... | .... | ... | ... |
| . | ... | .... | ... | .... | . . | ... |
| | ... | .... | ... | .... | ... | .. |
| 7 | .19 | .... | .74 | trace | .21 | . |
| | .002 | | .010 | | .003 | |
| 9 | .13 | .... | ... | .... | ... | .. |
| 2 | none | .... | trace | .... | ... | .. |
| . | F. 76 | .... | ... | .... | ... | .. |
| | .032 | | | | | |
| 2 | 99.59 | | 100.00 | 100.54 | 100.46 | 99. |

e), El Capitan, Yosemite Valley,

oscanose), Nevada Falls Trail, 99), p. 297, and *Bull.* 168, *U. S.*

amiatose), Walkerville Station, *ll.* 168, *U. S. Geol. Surv.*, p. 116.
(?)toscanose), Bloods Station, p. 294.
se), Cape Ann, Mass. *A. J. S.*, . S. WASHINGTON, JOUR. GEOL.,

(*f*) *Lep*
*Bull.* 168,
(*g*) *Lep*
way; rock
BRÖGGER,
(*h*) *Lep*
rock analy
PINSKI, *G*
(*i*) "Bi
*Geol.*, p. 2
(*j*) *Phl*
Hills, Wy

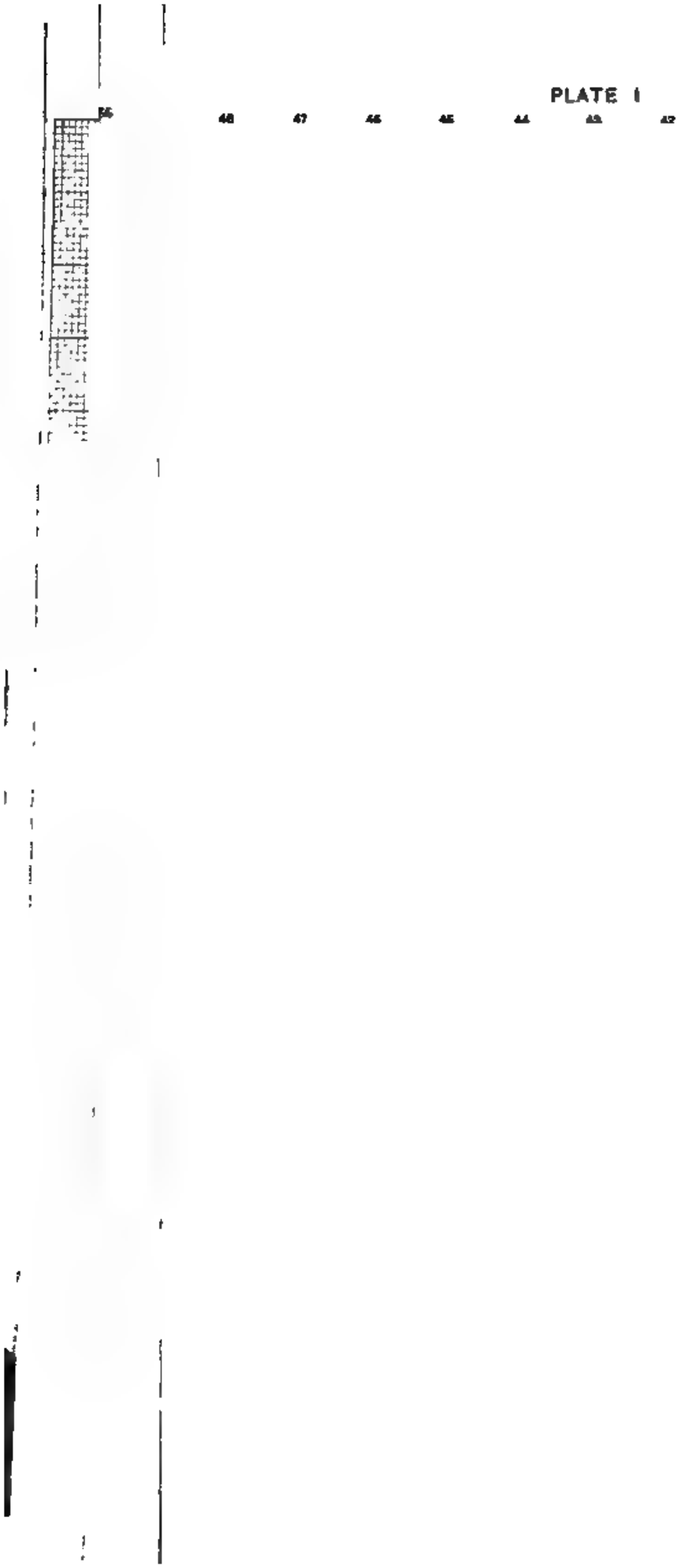
| | 6 | |
|---|---|---|
| rox. | Rock. | Pyrox. |
| .57 | 52.75 | 51.60 |
| .876 | | .860 |
| .33 | 22.55 | 1.92 |
| .013 | | .018 |
| .86 | 3.65 | 26.29 |
| .036 | | .164 |
| .23 | ... | 4.20 |
| .044 | | .058 |
| .36 | .15 | 1.15 |
| .309 | | .029 |
| .49 | 1.85 | 4.25 |
| .330 | | .076 |
| .80 | 8.10 | 8.89 |
| .061 | | .143 |
| .03 | 7.05 | 1.05 |
| .011 | | .011 |
| ... | 3.60 | .56 |
| ... | ... | ... |
| .18 | ... | ... |
| .024 | | |
| ... | ... | ... |
| ... | ... | ... |
| ... | ... | ... |
| ... | ... | ... |
| ... | ... | ... |
| .15 | ... | ... |
| .002 | | |
| ... | ... | ... |
| | ... | ... |
| ... | ... | ... |
| .00 | 99.70 | 99.91 |
| 227 | .... | .... |
| .. | .... | .... |

ysis *Bull.* 150 *U. S.*
*. S.*
ra de Tingua,
kove Grants, N. M.
*iageb.*

usch (ose), Falken-
llose) 346.
*Pal.* Barreros, rock
, do Poços de
rained, 126.
salt
ose).

# INDEX

PLATE I



A. Hoen & Co. Lith. Baltimore, Md.

SILICA

PLATE III